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Rare decays at B-factories

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Summary. — We report the latest results from *BABAR* and Belle on leptonic decays of B mesons and $B \to \mathrm{K}^{(*)}\nu\nu$.

PACS 13.20.-v – Leptonic, semileptonic, and radiative decays of mesons.
PACS 13.25.Hw – Decays of bottom mesons.

1. – Introduction

Purely leptonic decays of B mesons, like $B \to \tau\nu$, and the flavour-changing neutral-current decays $B \to K^{(*)}\nu\nu$, are interesting probes of new physics effects because their expression in the Standard Model (SM) is theoretically clean and possible contributions from physics beyond the SM may be of the same order of magnitude. In contrast to their favorable phenomenological condition, the experimental search of these decays is complicated from the presence of two to three neutrinos in the final state, weakening their experimental signature. Since at *BABAR* [1] and Belle [2] B-factories, B mesons are produced from the exclusive decays of $\Upsilon(4S) \to B\overline{B}$, a commonly adopted strategy is to reconstruct one of the two B mesons in clean decay modes first. After removing all the decay products of the fully reconstructed B meson (tag-B), the rest of the reconstructed event is searched for the low multiplicity signal B decay modes, requiring the absence of additional activity in the detector. The residual energy in the electromagnetic calorimeter (E_{extra}), calculated from clusters not associated to the tag-B or to the signal final state, is usually the most discriminating variable, and it is used in many analyses to extract the signal yield.

2. – Tag-B reconstruction methods

The tag-B is reconstructed using two methods, hadronic tagging or semileptonic tagging.

2˙1. *Hadronic tagging.* – In this case a tag-B is reconstructed in a set of hadronic decays $B \to MX$, where M denotes a $D^{(*)0}$, a $D^{(*)+}$ or a J/ψ, and X denotes a system of hadrons. Two kinematic variables are used to discriminate between correctly reconstructed tag-B candidates and mis-reconstructed events: the beam energy-substituted mass $m_{\rm ES} \equiv \sqrt{s/4 - p_B^2}$, and the energy difference $\Delta E \equiv E_B - \sqrt{s}/2$, where $\sqrt{s}$ is the total energy in the $\Upsilon(4S)$ center-of-mass system (CM) and p_B and E_B, respectively, denote the momentum and the energy of the tag-B candidate in the CM. Events with a correctly reconstructed tag-B are characterised by an $m_{\rm ES}$ distribution peaked at the nominal B mass, while the continuum events and combinatorial backgrounds are characterised by a smooth $m_{\rm ES}$ distribution.

2˙2. *Semileptonic tagging.* – In the case of semileptonic tags, a positively identified electron or muon l and a reconstructed $D^{(*)}$ are combined into a $D^{(*)}l$ pair to verify the consistency with a $B_{tag} \to D^{(*)}l\nu$, assuming one and only one undetected neutrino. Due to the presence of the neutrino, the tag-B direction cannot be determined, but four-momentum conservation requires the tag-B to lie on a cone around the $D^{(*)}l$ system in the CM. The cosine of the angle $\cos\theta_{B,D^{(*)}l}$ between the tag-B and the $D^{(*)}l$ momentum is given by $\cos\theta_{B,D^{(*)}l} = (\sqrt{s}E_{D^{(*)}l} - m_B^2 - m_{D^{(*)}l}^2)/(2p_{B_{tag}}p_{D^{(*)}l})$. Consistency with the semileptonic decay $B_{tag} \to D^{(*)}l\nu$ is imposed by requiring that $|\cos\theta_{B,D^{(*)}l}| < 1$.

3. – Leptonic decays of B mesons

The study of the purely leptonic decay $B \to \tau\nu$ is of particular interest to test the predictions of the SM and to probe new physics effects. It is sensitive to the product of the B meson decay constant f_B, and the absolute value of the Cabibbo-Kobayashi-Maskawa matrix element $|V_{ub}|$. Using the Lattice QCD calculation of $f_B = (189 \pm 4)$ MeV [3], and the measurement of $|V_{ub}|$ from charmless semileptonic B exclusive decays [4], the predicted SM value of the branching fraction is $\mathcal{B}_{SM}(B \to \tau\nu) = (0.66 \pm 0.13) \times 10^{-4}$. Using, instead, the measurement of $|V_{ub}|$ from inclusive charmless semileptonic B decays [4], the SM prediction is $\mathcal{B}_{SM}(B \to \tau\nu) = (1.22 \pm 0.12) \times 10^{-4}$. Therefore, the uncertainty in the SM prediction is dominated by the uncertainty in $|V_{ub}|$. The process is sensitive to possible extensions of the SM. For instance, in two-Higgs doublet models (2HDM) [5] and in minimal supersymmetric extensions [6] it can be mediated by a charged Higgs boson.

3˙1. *Recent searches of $B \to \tau\nu$.* – In the most recent search from *BABAR* [7] hadronic tag-B reconstruction and 467.8×10^6 $B\overline{B}$ pairs are used. The τ lepton is identified in the following modes: $\tau \to e\nu\nu$, $\tau \to \mu\nu\nu$, $\tau \to \pi\nu$, and $\tau \to \rho\nu$. The branching fraction is obtained by a simultaneous likelihood fit to the $E_{\rm extra}$ distribution in the four τ decay modes, with the background yields floating and the four signal yields constrained to the common branching fraction. An excess of events with respect to the expected background is found, excluding the null signal hypothesis at the level of 3.8 σ and corresponding to a branching fraction central value of $\mathcal{B}(B \to \tau\nu) = (1.83^{+0.53}_{-0.49}({\rm stat.}) \pm 0.24({\rm syst.})) \times 10^{-4}$.

Another analysis from *BABAR* [8] exploits the semileptonic tag-B reconstruction, providing a measurement based on a statistically independent data sample with respect to the hadronic tag analysis. Discriminating variables on signal, tag-B and event shapes are combined in a likelihood ratio, and the selection is optimised to the best upper limit. The branching ratio is extracted with a cut and count method. The background is estimated from a data sideband of $E_{\rm extra}$ distribution and scaled to the signal region using MC. This analysis measures a $\mathcal{B}(B \to \tau\nu) = (1.7 \pm 0.8 \pm 0.2) \times 10^{-4}$, at 2.3 σ.

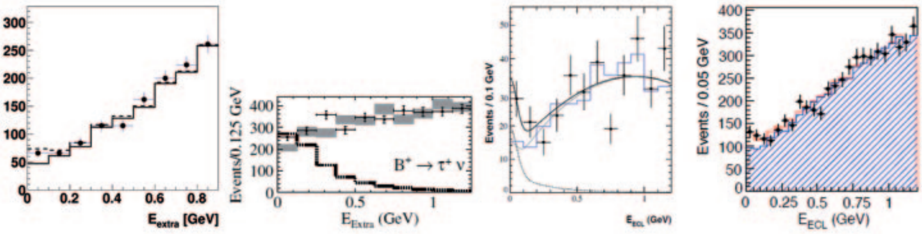

Fig. 1. – Distribution of E_{extra} for $B \to \tau\nu$ searches. Points with error bars are data, histograms are background expectations. From left to right: *BABAR* hadronic tags, *BABAR* semileptonic tags, Belle hadronic tags, Belle semileptonic tags.

The most recent published analysis from Belle [9] uses the semileptonic tag reconstruction and 657 million $B\overline{B}$ pairs. After tag-B reconstruction, exactly one charged track is required in the rest of the event, and particle identification criteria are used to assign the event to the $\tau \to e$, $\tau \to \mu$ or $\tau \to \pi$ category. Selection requirements are also applied to the signal track momentum and to $\cos\theta_{B,Dl}$. The signal yield is determined by means of a likelihood fit to the E_{extra} distribution. This analysis measures $\mathcal{B}(B \to \tau\nu) = (1.54^{+0.38}_{-0.37}(\text{stat.})^{+0.29}_{-0.31}(\text{syst.})) \times 10^{-4}$, at 3.6 σ. Belle also published an analysis using hadronic tagging [10] and 449 millions of $B\overline{B}$ pairs resulting in $\mathcal{B}(B \to \tau\nu) = (1.79^{+0.56}_{-0.49}(\text{stat.})^{+0.46}_{-0.51}(\text{syst.})) \times 10^{-4}$, at 3.5 σ. The distribution of E_{extra} in experimental data compared with background predictions, and the likelihood fit projection, are shown in fig. 1 for the four analyses described above.

4. – Flavour-changing neutral current $B \to \mathrm{K}^{(*)}\nu\nu$

The decays $B \to K\nu\nu$ arise from flavour-changing neutral currents (FCNC), which are forbidden at tree level in SM. The lowest-order SM processes contributing to these decays are W box and the Z penguin loop diagrams, predicting a branching fraction $\sim 4 \times 10^{-6}$. New physics contributions may enter at the same order as the SM. These contributions include: unparticle models, Minimal Supersymmetric extension of the SM at large $\tan\beta$, models with a single universal extra dimension, scalar Weakly Interacting Massive Particle (WIMP) dark matter and WIMP-less dark matter.

4·1. *Recent searches of* $B \to K^{(*)}\nu\nu$. – The most recent published analysis from *BABAR* [11] uses 459 millions of $B\overline{B}$ pairs and the semileptonic tag-B reconstruction, to search for $B^+ \to K^+\nu\nu$ or $B^0 \to K_S\nu\nu$, with $K_S \to \pi^+\pi^-$. For the K^+ (K_S) analysis 26 (38) discriminating variables exploiting the missing energy, event shape, kinematics and quality of the tag reconstruction are combined in a multivariate discriminator based on Boosted Decision Trees. The comparison of the data and background expectation (from MC) of the distribution of this discriminator is used to extract the signal yield.

Another analysis from *BABAR* [12] uses 454 millions of $B\overline{B}$ pairs and exploits both the hadronic and semileptonic tag reconstruction, to search for $B^+ \to K^{*+}\nu\nu$ and $B^0 \to K^{*0}\nu\nu$ decays. In the data sample where the tag-B is reconstructed in hadronic decay modes, discriminating variables are combined in a neural network and the distribution of the output of the network is used to extract the signal yield. For the data sample with semileptonic tag-B candidates, the signal yield is determined by means of a maximum-likelihood fit to the E_{extra} distribution.

Table I. – $B \to \tau\nu$ *and* $B \to K^{(*)}\nu\nu$ *published results from BABAR and Belle Collaborations.*

Process	*BABAR* measurement ($\times 10^{-5}$)	Belle measurement ($\times 10^{-5}$)
$\mathcal{B}(B \to \tau\nu)$ hadronic tags	$18 \pm 5 \pm 2$	$18^{+6}_{-5} \pm 5$
$\mathcal{B}(B \to \tau\nu)$ semileptonic tags	$17 \pm 8 \pm 2$	$15 \pm 4 \pm 3$
$\mathcal{B}(B^+ \to K^+\nu\nu)$	< 1.6	< 1.4
$\mathcal{B}(B^0 \to K^0\nu\nu)$	< 5.6	< 16
$\mathcal{B}(B^+ \to K^{*+}\nu\nu)$	< 8	< 14
$\mathcal{B}(B^+ \to K^{*0}\nu\nu)$	< 12	< 34

Belle Collaboration published a search [13] for $B \to h\nu\nu$ decays, where h is an hadron, including K^+, K^{*+}, K^{*0}, K^0_S, using 535 millions of $B\overline{B}$ pairs and the hadronic tag-B reconstruction. The analysis follows a cut and count strategy, with the signal selection based on the kinematics, topology and a π^0 veto. The background is estimated from a data sideband defined by $E_{\text{extra}} > 450\,\text{MeV}$ and scaled to the signal region ($E_{\text{extra}} < 300\,\text{MeV}$) using MC.

All the searches described above do not find a statistically significant excess in data with respect to background expectations.

5. – Conclusions

Leptonic B decays and $B \to K^{(*)}\nu\nu$ are excellent probes of new physics, but experimentally challenging. Table I shows the results from *BABAR* and Belle discussed in this paper. Searches of $B \to K^{(*)}\nu\nu$ provided only upper limits to the branching fraction, still above the SM prediction. $B \to \tau\nu$ decay has been observed and the branching fraction is still consistent with the SM expectation, though with some tension, and already setting strong constraints in models of physics beyond the SM as the 2HDM type II.

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