

Review of B_u leptonic decays

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This paper reviews the status of searches and measurements of B_u leptonic decays, concentrating on the most recent results obtained at B -factories. We will describe studies of decays of the type $B^+ \rightarrow \ell^+ \nu_\ell$ and $B^+ \rightarrow \ell^+ \nu_\ell \gamma$.

1. Introduction

There are several reasons for studying purely leptonic decays of charged B mesons. Such processes are rare but they have clear experimental signatures due to the presence of a highly energetic lepton in the final state. The theoretical predictions are very clean due to the absence of hadrons in the final state. These features make such decays the ideal ground to look for deviations from the Standard Model (SM) predictions hoping for some signs of New Physics (NP). Furthermore, as described in Sec. 2, measuring the branching fraction (BF) of these modes allows direct insight into some of the fundamental parameters of the theory, that are not easily accessible otherwise.

In this review we will describe some of the latest results on leptonic and radiative leptonic decays of charged B mesons obtained at the B -factory experiments, Belle [1] and BaBar [2], both collecting $B\bar{B}$ pairs at the $e^+e^- \rightarrow \Upsilon(4S)$ resonance. The common characteristic of all the analyses described is the presence of one (for electronic and muonic modes) or more (for the tauonic mode) neutrinos in the signal B (B_{sig}). To suppress background and constrain kinematically the B_{sig} reconstruction, the common solution is to reconstruct the other B meson in the event, usually referred to as tag, companion or recoil B (B_{tag} in our notation). The B_{tag} reconstruction can be performed inclusively, by reconstructing and identifying all particles in the event that do not belong to the signal and using them to form a B candidate, or exclusively, by selecting several decay modes adding up to a reasonable BF and reconstructing B_{tag} in these modes. A great reduction of the continuum background is obtained by selecting events in which the B_{tag} candidate is kinematically consistent with a B meson issued from the decay of a $\Upsilon(4S)$. The selection is usually performed on the two following variables: the beam constrained mass (called M_{bc} by Belle and m_{ES} by BaBar) $M_{\text{bc}} = \sqrt{E_{\text{beam}}^2 - |\vec{p}_B^*|^2}$ and $\Delta E = E_B^* - E_{\text{beam}}$, where \vec{p}_B^* and E_B^* are the momentum and energy of B_{tag} , all variables being evaluated in the Center-of-Mass (CM) frame. For $B\bar{B}$ events, M_{bc} is centered at the value of the B mass and ΔE at zero. The advantage of exclusive B_{tag} selections is the very powerful suppression of background, at the price of a relatively small signal efficiency. Inclusive

selections can give higher efficiencies, but are better suited for channels in which the signal signature allows a good separation from background. As we will describe in the following, both techniques have been pursued with success by Belle and BaBar.

2. Searches for $B^+ \rightarrow \ell^+ \nu_\ell$ decays

Purely leptonic decays of charged B mesons proceed in the SM via the W -mediated annihilation tree diagram, with a branching fraction given by:

$$\text{BF}(B^+ \rightarrow \ell^+ \nu_\ell) = \frac{G_F^2 m_B}{8\pi} m_\ell^2 \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B, \quad (1)$$

where τ_B is the B meson lifetime, f_B is the B decay constant and V_{ub} an element of the CKM-matrix. These modes are very interesting because they give direct access to the product $f_B \times V_{ub}$, from which one can extract a measurement of f_B , since V_{ub} is measured in other B decay modes [3]. The SM expectation for $B^+ \rightarrow \tau^+ \nu_\tau$ is $\text{BF}(B^+ \rightarrow \tau^+ \nu_\tau) = (1.59 \pm 0.40) \times 10^{-4}$, assuming for V_{ub} the value $(4.39 \pm 0.33) \times 10^{-3}$ determined by inclusive charmless semileptonic B decay data [3], $\tau_B = 1.643 \pm 0.010$ ps [3], and $f_B = 0.216 \pm 0.022$ GeV obtained from lattice QCD calculations [4]. Decays to lighter leptons are helicity suppressed, and are their BF are predicted to be $(4.7 \pm 0.7) \times 10^{-7}$ for $B^+ \rightarrow \mu^+ \nu_\mu$ and $(1.1 \pm 0.2) \times 10^{-11}$ for $B^+ \rightarrow e^+ \nu_e$. Allowing for NP decay amplitudes, measurements of these processes can give stringent limits on important parameters of such SM extensions, such as the mass of the charged Higgs boson and $\tan\beta$ (the ratio of vacuum expectation values of the two Higgs doublets) in the minimal supersymmetric SM (MSSM)[5].

2.1. Searches for $B^+ \rightarrow \tau^+ \nu_\tau$ decay

Both Belle and BaBar have recently presented results of searches for the $B^+ \rightarrow \tau^+ \nu_\tau$ decay. Compared to the lighter leptonic modes, this channel has the disadvantage of additional neutrinos (one or more, depending on the τ decay mode).

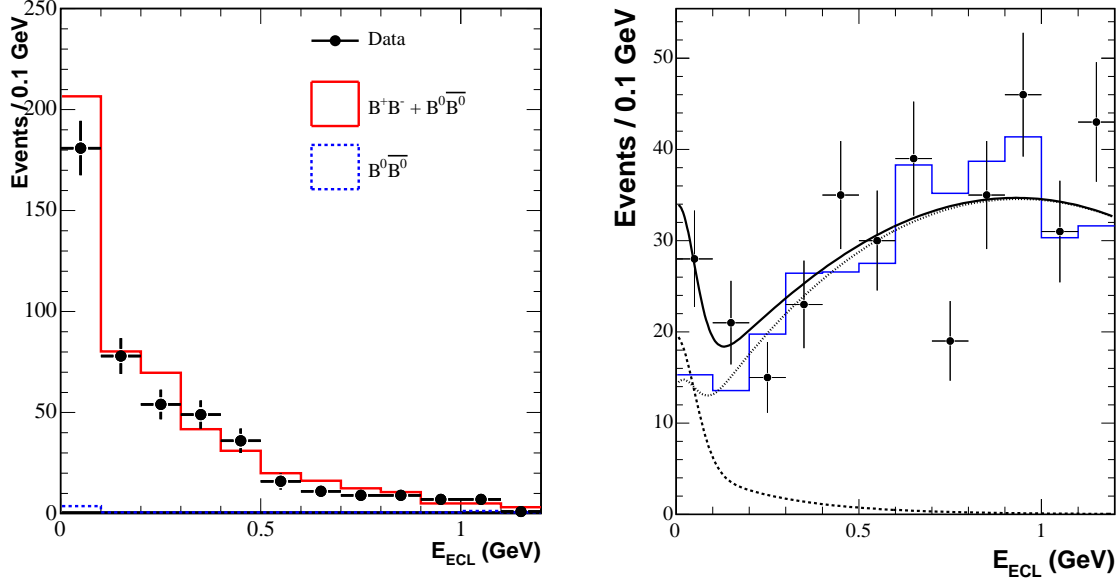


Figure 1: Search for $B^+ \rightarrow \tau^+ \nu_\tau$ in Belle. Left: the E_{ECL} distribution in the double tagged control channel, showing good agreement of MC expectation (histograms) and data (points). Right: E_{ECL} distribution in the data after all selection criteria. The data and background MC samples are represented by the points and the solid histogram, while the solid curve shows the result of the fit with the sum of the signal (dashed) and background (dotted) contributions.

2.1.1. Belle's first evidence for $B^+ \rightarrow \tau^+ \nu_\tau$ decay

The Belle analysis [6] is based on a data sample of 414 fb^{-1} and it employs a full reconstruction of B_{tag} in the following decay modes: $B^- \rightarrow D^{(*)0}\pi^-, D^{(*)0}\rho^-, D^{(*)0}a_1^-,$ and $D^{(*)0}D_s^{*-}$. The D^0 mesons are reconstructed as $D^0 \rightarrow K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^-\pi^+\pi^+, K_S^0\pi^0, K_S^0\pi^-\pi^+, K_S^0\pi^-\pi^+\pi^0$ and K^-K^+ , and the D_s^- mesons are reconstructed as $D_s^- \rightarrow K_S^0K^-$ and $K^+K^-\pi^-$. The D^{*0} and D_s^{*-} mesons are reconstructed in $D^{*0} \rightarrow D^0\pi^0, D^0\gamma,$ and $D_s^{*-} \rightarrow D_s^-\gamma$ modes. The B_{tag} selection yields a sample of about $6.8 \times 10^5 B\bar{B}$ events with a purity of 55%. In this sample, particles that are not assigned to B_{tag} are assigned to B_{sig} and a decay to a τ and a neutrino is looked for. The τ lepton is identified in five decay modes, $\mu^-\bar{\nu}_\mu\nu_\tau, e^-\bar{\nu}_e\nu_\tau, \pi^-\nu_\tau, \pi^-\pi^0\nu_\tau$ and $\pi^-\pi^+\pi^-\nu_\tau,$ which taken together correspond to 81% of all τ decays. Further background suppression is obtained by applying requirements on the magnitude and direction of the missing momentum.

The most powerful variable for separating signal and background is the remaining energy in the electromagnetic calorimeter (ECL), denoted as E_{ECL} , which is the sum of the energies of neutral clusters that are not associated with either the B_{tag} or the π^0 candidate from the $\tau^- \rightarrow \pi^-\pi^0\nu_\tau$ decay. For signal events, E_{ECL} must be either zero or a small value arising from beam background hits, therefore, signal events peak at low E_{ECL} . On the other hand, background events are dis-

tributed toward higher E_{ECL} due to the contribution from additional neutral clusters. A validation of the E_{ECL} simulation is performed using a control sample of double tagged events where the B_{tag} is fully reconstructed as described above and B_{sig} is reconstructed in the decay chain, $B^+ \rightarrow \bar{D}^{*0}\ell^+\nu$ ($\bar{D}^{*0} \rightarrow \bar{D}^0\pi^0$), followed by $\bar{D}^0 \rightarrow K^+\pi^-$ or $K^+\pi^-\pi^+\pi^-$ where ℓ is a muon or an electron. Fig. 1 (left) shows the E_{ECL} distribution in the control sample for data and the scaled Monte Carlo (MC) simulation, with very good agreement between the two. Fig. 1 (right) shows the E_{ECL} distribution obtained after all selections are applied and with all τ decay modes combined. One can see a significant excess of events in the E_{ECL} signal region below $E_{\text{ECL}} < 0.25 \text{ GeV}$. The signal yield is extracted by fitting the E_{ECL} distributions to the sum of the expected signal and background shapes extracted from the MC simulations, and including a background component peaking at $E_{\text{ECL}} = 0$. The combined fit for all five τ decay modes gives $17.2_{-4.7}^{+5.3}$ signal events in the signal region; the corresponding BF, including systematic uncertainties is:

$$\text{BF}(B^+ \rightarrow \tau^+ \nu_\tau) = (1.79_{-0.49}^{+0.56}(\text{stat})_{-0.51}^{+0.46}(\text{syst})) \times 10^{-4}. \quad (2)$$

The significance is 3.5σ , representing the first evidence of the purely leptonic decay $B^+ \rightarrow \tau^+ \nu_\tau$. Using the value of $|V_{ub}|$ from [3], Belle obtains $f_B = 0.229_{-0.031}^{+0.036}(\text{stat})_{-0.037}^{+0.034}(\text{syst}) \text{ GeV}$, the first direct determination of the B meson decay constant. A mea-

surement of $\text{BF}(B^+ \rightarrow \tau^+ \nu_\tau)$ can directly be translated into a constraint on parameters of two-Higgs-doublet models of type II [5], via the formula:

$$\text{BF}_{\text{MSSM}}(B^+ \rightarrow \tau^+ \nu_\tau) = \text{BF}_{\text{SM}}(B^+ \rightarrow \tau^+ \nu_\tau) \times \left(1 - \frac{m_B^2}{m_H^2} \tan^2 \beta\right)^2 \quad (3)$$

which relates the SM value to the MSSM one via a factor depending only on the mass of the B meson and of the charged Higgs (m_H) and on $\tan\beta$. The Belle measurement translates in the constraints in the m_H - $\tan\beta$ plane that are illustrated in Fig. 2.

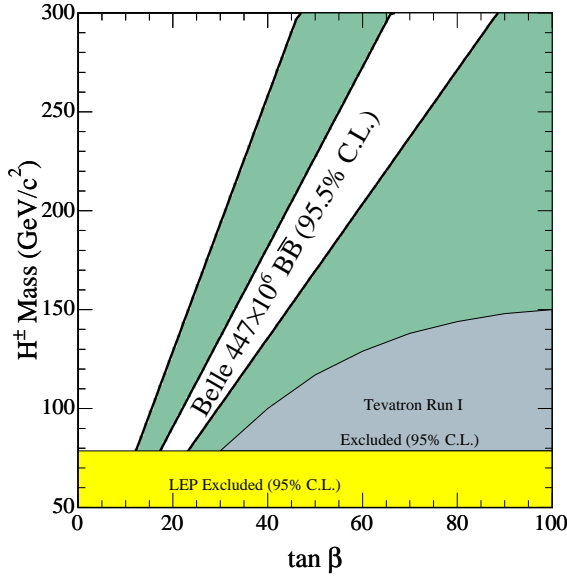


Figure 2: Exclusion plot at 95% C.L. in the m_H^\pm - $\tan\beta$ plane derived from the Belle measurement of the $B^+ \rightarrow \tau^+ \nu_\tau$ BF. The region excluded by Belle is in green. Areas excluded by other experiments are also shown in different colors.

2.1.2. BaBar's $B^+ \rightarrow \tau^+ \nu_\tau$ analyses

The BaBar collaboration has recently presented [7] the results of two searches of the $B^+ \rightarrow \tau^+ \nu_\tau$ decay, both based on the same data sample of 383×10^6 $B\bar{B}$ pairs, exploiting different selections for the B_{tag} candidates and thus yielding statistically independent results.

The first analysis [8] is based on the exclusive reconstruction of semileptonic B_{tag} decays of the type $B^- \rightarrow D^0 \ell^- \bar{\nu}_\ell X$, where ℓ denotes either an electron or a muon, and X can be either nothing or a π^0 or photon from a higher mass charm state decay which is not explicitly included in B_{tag} . D^0 candidates are reconstructed in four decay modes: $K^- \pi^+$, $K^- \pi^+ \pi^- \pi^+$, $K^- \pi^+ \pi^0$, and $K_S^0 \pi^+ \pi^-$. This choice

of B_{tag} yields a higher efficiency than full reconstruction of $B^- \rightarrow D^{*0} \ell^- \bar{\nu}_\ell$, but a slightly lower purity. After selection of tagged events, the τ from the signal side is looked for in the remaining particles of each event, in the modes $\tau^+ \rightarrow e^+ \nu \bar{\nu}$, $\tau^+ \rightarrow \mu^+ \nu \bar{\nu}$, $\tau^+ \rightarrow \pi^+ \bar{\nu}$, and $\tau^+ \rightarrow \pi^+ \pi^0 \bar{\nu}$, constituting approximately 71% of the total τ decay width. Background rejection and validation of the B_{tag} selection are performed using techniques similar to the ones described above. The final discriminating variable is the remaining energy (E_{extra}), calculated by summing the CM energy of neutral clusters and tracks that are not associated with either B_{tag} or B_{sig} . The E_{extra} distributions in data and MC are shown in Fig. 3 for the four τ decay modes separately (left) and for the combined sample (right). Mode dependent signal regions are chosen to optimize signal significance in the range $E_{\text{extra}} < 0.25$ – 0.48 GeV, and the expected background in these regions is evaluated by comparing data and MC in the $E_{\text{extra}} > 0.5$ GeV sideband and extrapolating using the MC shape. A summary of expected background and observed signal events is presented in Table I. Given that the signal observed

Table I BaBar's semileptonic $B^+ \rightarrow \tau^+ \nu_\tau$ analysis: observed number of on-resonance data events in the signal region and number of expected background events.

τ	Expected background	Observed events
decay mode	events	in on-resonance data
$\tau^+ \rightarrow e^+ \nu \bar{\nu}$	44.3 ± 5.2	59
$\tau^+ \rightarrow \mu^+ \nu \bar{\nu}$	39.8 ± 4.4	43
$\tau^+ \rightarrow \pi^+ \bar{\nu}$	120.3 ± 10.2	125
$\tau^+ \rightarrow \pi^+ \pi^0 \bar{\nu}$	17.3 ± 3.3	18
All modes	221.7 ± 12.7	245

is not significant, BaBar quotes for the BF both a measurement,

$$\text{BF}(B^+ \rightarrow \tau^+ \nu_\tau) = (0.9 \pm 0.6(\text{stat.}) \pm 0.1(\text{syst.})) \times 10^{-4} \quad (4)$$

and a 90% Confidence Level (CL) upper limit,

$$\text{BF}(B^+ \rightarrow \tau^+ \nu_\tau) < 1.7 \times 10^{-4}. \quad (5)$$

Another search for the $B^+ \rightarrow \tau^+ \nu_\tau$ decay is performed by BaBar by following a strategy very similar to the one just presented, but with a different selection of B_{tag} . Preliminary results of this analysis were presented for the first time at this conference [7]. The B_{tag} candidate is reconstructed in hadronic modes of the type $B^- \rightarrow D^{(*)0} X^-$, with $D^{*0} \rightarrow D^0 \pi^0, D^0 \gamma$ and X^- can be made of a combination of up to five charged pions and kaons, up to two π^0 mesons and up to two K_S^0 mesons. The same τ decay modes as in the semileptonic-tag study are reconstructed in the signal side, and the results obtained are summarized in Fig. 4. The slight excess of signal visible in the

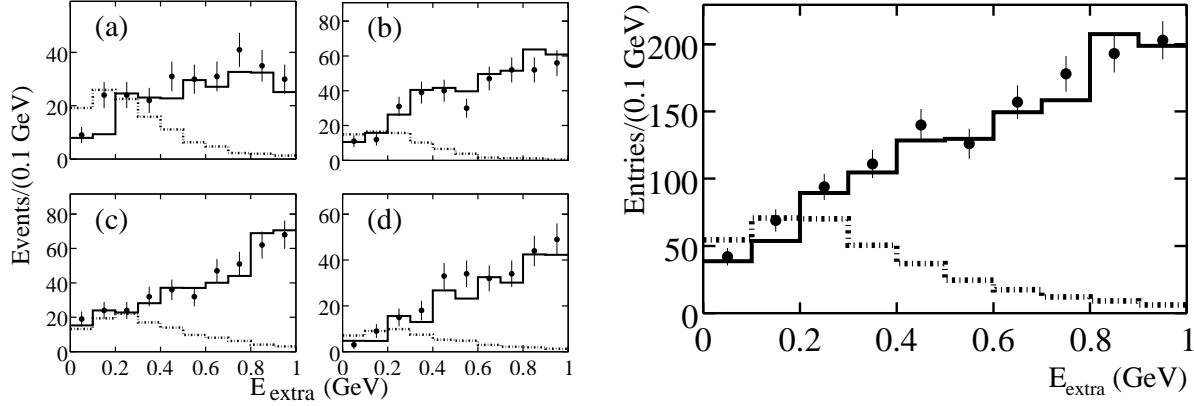


Figure 3: Left: E_{extra} distributions in the BaBar semileptonig-tag $B^+ \rightarrow \tau^+ \nu_\tau$ analysis for (a) $\tau^+ \rightarrow e^+ \nu_\tau$, (b) $\tau^+ \rightarrow \mu^+ \nu_\tau$, (c) $\tau^+ \rightarrow \pi^+ \nu_\tau$, and (d) $\tau^+ \rightarrow \pi^+ \pi^0 \nu_\tau$. Right: all four modes combined. Background MC (solid histogram) is rescaled to match the normalization of the on-resonance data (black dots) in the E_{extra} sideband region. $B^+ \rightarrow \tau^+ \nu_\tau$ signal MC (dotted histogram) is normalized to a branching fraction of 10^{-3} and shown for comparison.

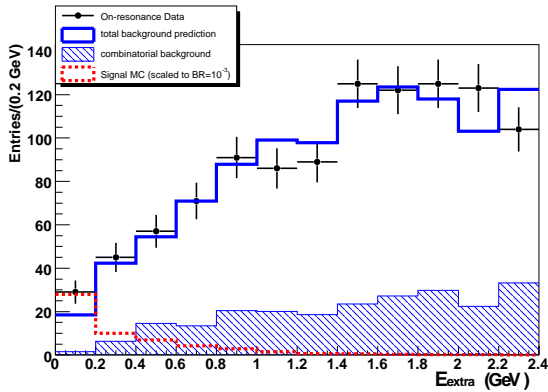


Figure 4: E_{extra} distribution for the BaBar hadronic-tag $B^+ \rightarrow \tau^+ \nu_\tau$ analysis, for all τ decay modes combined.

first bin of the plot corresponds to a total of 24 observed events in the (mode dependent) signal window with an expected background of about 14 events. The corresponding measured BF is:

$$\text{BF}(B^+ \rightarrow \tau^+ \nu_\tau) = (1.8_{-0.9}^{+1.0}(\text{stat.}+\text{bkg.}) \pm 0.3(\text{syst.})) \times 10^{-4}, \quad (6)$$

where the first error includes the statistical error and the uncertainty on the expected background. The significance of this measurement, including all uncertainties, is of 2.2σ . A combination of this result with the one obtained from the semileptonic-tag analysis (Eq. 4) yields:

$$\text{BF}(B^+ \rightarrow \tau^+ \nu_\tau) = (1.20_{-0.38}^{+0.40}(\text{stat.})_{-0.30}^{+0.29}(\text{bkg.}) \pm 0.22(\text{syst.})) \times 10^{-4}, \quad (7)$$

corresponding to a significance of 2.6σ . This result is in good agreement with the Belle measurement described above (Eq. 2).

2.2. Searches for $B^+ \rightarrow e^+ \nu_e$ and $B^+ \rightarrow \mu^+ \nu_\mu$ decays

The Belle search for $B^+ \rightarrow e^+ \nu_e$ and $B^+ \rightarrow \mu^+ \nu_\mu$ decays [9] is based on an inclusive reconstruction of B_{tag} , in a data sample of 253 fb^{-1} . The strategy is to first identify a highly energetic lepton (electron or muon) and then check consistency of all the other particles in the event with the hypothesis that they come from the decay of a B meson, by defining an acceptance window in the $M_{\text{bc}}-\Delta E$ plane. Continuum background is reduced by imposing requirements on the transverse component and the polar angle of the missing momentum, corresponding to the neutrino in the signal decay. Further suppression is obtained by exploiting the event shape difference between continuum and $B\bar{B}$ events. The main variable used to select signal is the lepton momentum in the B_{sig} rest frame, p_ℓ^B , which for the signal is expected to be approximately equal to half of the B meson mass. A plot of p_ℓ^B for the muon mode after all selections are applied is shown in Fig. 5 (left). Similar distributions are found for the electron mode. The signal yield is extracted from a fit to the B_{tag} M_{bc} distribution. The distribution and fit curves are shown in Fig. 5 (right) for the muon mode. No evidence of signal is found in any of the modes, and the following upper limits are obtained on the branching fractions:

$$\text{BF}(B^+ \rightarrow \mu^+ \nu_\mu) < 1.7 \times 10^{-6} \quad (90\% \text{ CL}) \quad (8)$$

$$\text{BF}(B^+ \rightarrow e^+ \nu_e) < 9.8 \times 10^{-7} \quad (90\% \text{ CL}), \quad (9)$$

including the effect of the systematic uncertainties.

The Babar's analysis [10] is based on a sample of 209 fb^{-1} , and proceeds through a full reconstruction of the B_{tag} in the modes $B^- \rightarrow D^{(*)0} X^-$, where X can contain any number of pions and kaons. The signal

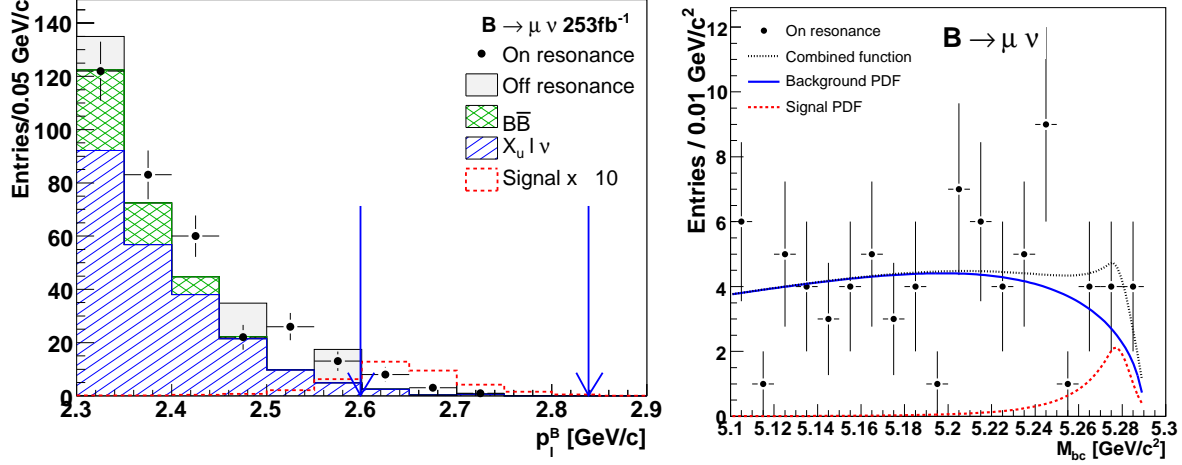


Figure 5: Belle $B^+ \rightarrow \ell^+ \nu_\ell$ analysis. Left: p_ℓ^B distributions for the signal candidates in the muon mode. Points show the on-resonance data, and solid histograms show the expected background due to rare $B \rightarrow X_u \ell \nu$ decays (hatched, from MC); other $B\bar{B}$ events, principally $B \rightarrow X_c \ell \nu$ decays (cross-hatched, also from MC); and continuum events (light shaded, taken from scaled off-resonance data). Dashed histograms are MC $B \rightarrow \ell \nu$ signals that are obtained by multiplying the SM expectations by a factor of 10. The arrows show the signal region. Right: M_{bc} distribution in the muon mode for selected events and fit result (dotted line) as a sum of signal (dashed) and background (solid) contributions.

selection and background suppression are carried out in a similar fashion to what described for the Belle's analysis above. Events with $E_{\text{extra}} < 1.2$ GeV are finally selected (see Fig. 6(left)) and a signal window is defined in the distribution of signal lepton momentum in the B_{sig} rest frame. No data points are selected in the signal window (see Fig. 6(right)) and this leads to the following upper limits, including systematic uncertainties:

$$\text{BF}(B^+ \rightarrow \mu^+ \nu_\mu) < 6.2 \times 10^{-6} \quad (90\% \text{ CL}) \quad (10)$$

$$\text{BF}(B^+ \rightarrow e^+ \nu_e) < 7.9 \times 10^{-6} \quad (90\% \text{ CL}). \quad (11)$$

3. Searches for $B^+ \rightarrow \ell^+ \nu_\ell \gamma$

The presence of the photon in decays of the type $B^+ \rightarrow \ell^+ \nu_\ell \gamma$ can lift the helicity suppression that has so far prevented the observation of the $B^+ \rightarrow \ell^+ \nu_\ell$ decay in electronic and muonic modes. The $B^+ \rightarrow \ell^+ \nu_\ell \gamma$ BF's are therefore independent of lepton flavour up to factors of the order $(m_\ell/m_B)^2$. The disadvantage of this type of decays is that the theoretical description of the radiative process is not as straightforward as the one outlined in Sec. 2, and therefore interpretation of results cannot be obtained without some degree of model dependence. Searches for $B^+ \rightarrow \ell^+ \nu_\ell \gamma$ decays with ℓ a muon or an electron, have been performed by CLEO [11], using a model for the signal [12] that predicted BF in the range $1-4 \times 10^{-6}$. Examining a data sample corresponding to 2.5 fb^{-1} , they extract the following upper limits at

90% CL:

$$\text{BF}(B^+ \rightarrow \mu^+ \nu_\mu \gamma) < 5.2 \times 10^{-5} \quad (12)$$

$$\text{BF}(B^+ \rightarrow e^+ \nu_e \gamma) < 2.0 \times 10^{-4}. \quad (13)$$

Preliminary results on the same channels have also been recently presented by BaBar, though based on different theoretical assumptions [13, 14]. BaBar measures a partial BF (ΔBF) in a restricted region of the phase space defined by $1.875 < E_\ell < 2.850$ GeV, $0.45 < E_\gamma < 2.35$ GeV and $\cos\theta_{\ell\gamma} < -0.36$, where E_ℓ and E_γ are the CM-energies of the signal lepton and photon and $\theta_{\ell\gamma}$ is the angle between them evaluated in the CM frame. In a sample of 210.5 fb^{-1} , the signal is formed selecting the highest CM-energy lepton and the highest CM-energy photon candidates; remaining particles in the event are used for an inclusive reconstruction and selection of the recoiling B_{tag} . After background rejection, the signal is extracted by maximizing a likelihood function defined by counting data events in four regions (one signal region and three sidebands, as shown in Fig. 7) in the plane formed by the B_{tag} m_{ES} and by the difference between the reconstructed neutrino candidate's energy and the magnitude of its 3-momentum in the CM frame (Δ_{EP}). No excess of events is observed over the expected background, and the following 90% CL Bayesian upper limits are extracted for ΔBF , assuming flat priors in BF, for separate channels and for their combination:

$$\Delta\text{BF}(B^+ \rightarrow \mu^+ \nu_\mu \gamma) < 2.1 \times 10^{-5} \quad (14)$$

$$\Delta\text{BF}(B^+ \rightarrow e^+ \nu_e \gamma) < 2.8 \times 10^{-5} \quad (15)$$

$$\Delta\text{BF}(B^+ \rightarrow \ell^+ \nu_\ell \gamma) < 2.3 \times 10^{-5}. \quad (16)$$

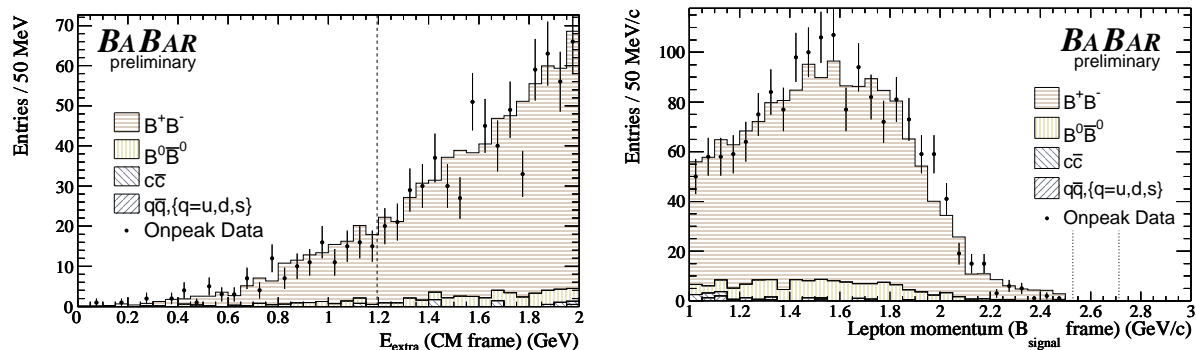


Figure 6: Distribution of E_{extra} (left) and of the lepton momentum in the B_{sig} rest frame (right) for the $B^+ \rightarrow \ell^+ \nu_\ell$ analysis in BaBar. Histograms show the different components of the expected backgrounds, points are the selected events in the data.

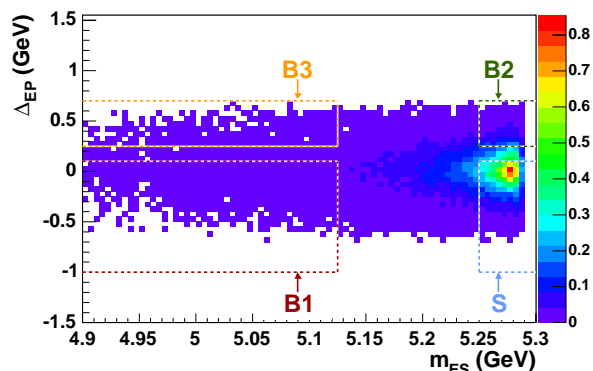


Figure 7: Search for $B^+ \rightarrow \ell^+ \nu_\ell \gamma$ in BaBar. Electron channel Δ_{EP} versus m_{ES} distribution from signal MC. The signal (S) and the three sideband regions (B1, B2, B3) are drawn as dashed rectangles. The color scale represents the relative content of each bin.

Within the theoretical model of Ref. [14], the last limit can be translated to an upper limit on the total BF: $\text{BF}(B^+ \rightarrow \ell^+ \nu_\ell \gamma) < 5.0 \times 10^{-6}$ at 90% CL.

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