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Purely leptonic and radiative leptonic decays from the e^+e^- B-factories

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Purely leptonic decays of B mesons provide opportunity to test the Standard Model (SM) and search for new physics (NP) beyond the SM. For instance, in some NP hypotheses, $B^+ \to \tau^+\upsilon_\tau$ and $B^+ \to l^+\upsilon_l$ can be influenced via exchange of a new charged particle such as a charged Higgs boson from supersymmetry or from two-Higgs doublet models. We present the recent results on purely leptonic and radiative leptonic decays of B mesons from the e^+e^- B-factory experiments, BaBar and Belle. In particular, we focus on the decays $B^+ \to \tau^+\upsilon_\tau$, $B^+ \to l^+\upsilon_l$, and $B^+ \to l^+\upsilon_l\gamma$. The Belle experiment has collected 772 million B-meson pairs produced by the KEKB energy-asymmetric e^+e^- collider at the $\Upsilon(4S)$ resonance, and the Babar experiment has collected 467.8 million B-meson pairs produced by the SLAC PEP-II.

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[1] Speaker

1. Introduction

In the Standard Model (SM), B meson's purely leptonic decay is suppressed by helicity suppression. Decay width of $B^+ \to \mu^+ \upsilon_\mu$ and $B^+ \to e^+ \upsilon_e$ are severely suppressed because of small lepton mass. Since the purely leptonic decays can be cleanly calculated in the SM, any deviation of measurement from the Standard Model prediction will be an indication of new physics (NP) beyond the SM. Possible candidates are two-Higgs doublet models (2HDM)[1] as in minimal super-symmetric SM (MSSM)[2] when charged Higgs boson takes the place of the W^+ boson.

The radiative leptonic decays $B^+ \to l^+ \upsilon_l \gamma \; (l = e, \mu)$ is determined by the first inverse moment λ_B^{-1}, where λ_B describes the quark momentum distribution in the B meson. If we measure branching fraction of $B^+ \to l^+ \upsilon_l \gamma$, we can give constraints to λ_B.

This article presents recent results of $B^+ \to \tau^+ \upsilon_\tau$, $B^+ \to l^+ \upsilon_l$, and $B^+ \to l^+ \upsilon_l \gamma$ from the $\Upsilon(4S) \to B\overline{B}$ Belle[3] 771 fb^{-1}and Babar[4] 433 fb^{-1}.

2. Reconstruction methods

Common problem to search those decays is missing momentum from the neutrinos. So we reconstruct one side of B meson named B_{tag}. Then, we can study missing neutrinos in other B meson because Υ(4S) decays into a pair of B meson. From B_{tag} reconstruction, we can obtain powerful kinematic variables that help signal extraction. $E_{ECL} (E_{extra})$ is remaining energy of calorimetor after subtraction energy from B_{tag} and signal-B side. For signal decay, we expect 0 GeV peak. $M_{bc} (m_{ES})$ is defined from beam energy and momentum of B_{tag}, it helps test magnitude of B_{tag} momentum.

We use two independent tags, one is hadronic tag and another is semileptonic tag.

Hadronic tag uses known b → c decay modes without neutrino, so B_{tag} is completely reconstructed. This character brought low effciency, high purity, and good momentum resolution of signal side charged particle. Belle uses 615 kind of channels to reconctruct charged B meson and uses network output (o_{tag}) of the multivariate selection algorithm while Babar does not use. Babar's reconstruction channel is different for each analysis.

Semileptonic tag uses B → $D^{(*)} l \nu \; (l = e, \mu)$ where $D^{(*)}$ meson is reconstructed from hadronic modes. Only one massless particle is missing in the recontruction decay. This causes less clear momentum resolution compared with hadronic tag.

3. Results

3.1 $B^+ \to \tau^+ \upsilon_\tau$

There are three recent results for $B^{+} \to \tau^{+}\upsilon_{\tau}$, using hadronic or semileptonic tag from Belle and Babar. The decay of $B^{+} \to \tau^{+}\upsilon_{\tau}$ is challenge since τ^{+} produces additional invisible particles. From all papers, τ^{+} from signal B meson decay is recoiled with $l^{+}\nu\nu(l = e, \mu)$, πν, and $\rho(\pi\pi^{0})\nu$.

3.1.1 $B^{+} \to \tau^{+}\upsilon_{\tau}$ with hadronic tag

At Babar, B_{tag} energy condition is required so that energy difference from beam energy should be minimized. Ratio between 2nd and 0th of Fox-Wolfram moments condition applied to prevent $e^{+}e^{-} \to \tau^{+}\tau^{-}$ backgrounds. Continuum backgrounds are rejected from the consine of the angle in the CM frame between the thrust axis of the B_{tag} candidates and the thrust axis of the remaing charged and neutral particles. Signal is extracted by an extended unbinned maximum likelihood fit to the measured E_{extra} distribution. The obtained branching fraction combining used sub-decay modes is $\mathcal{B}(B^{+} \to \tau^{+}\upsilon_{\tau}) = (1.83^{+0.53}_{-0.49} \pm 0.24) \times 10^{-4}$ with 3.8 σ significance[5].

At Belle, B_{tag} which has best network output is selected. To suppress background contamination from K_{L}'s, we explicitly veto the events containing K_{L} candidates. The efficiency of the K_{L} veto is calibrated by using the measured decay chain of $D^{0} \to \phi K_{S}$, and $\phi \to K_{L}K_{S}$. As a result of K_{L} veto, we get about 5% improve in the expected sensitivity. The $B^{+} \to \tau^{+}\upsilon_{\tau}$ signal is extracted by using two-dimensional extended maximum likelihood fit to E_{ECL} and $M^{2}_{miss} = (E_{CM} - E_{B_{tag}} - E_{B_{sig}})^{2} - |\vec{p}_{B_{tag}} + \vec{p}_{B_{sig}}|^{2}$ as shown in Figure 1. Obtained branching fraction is $\mathcal{B}(B^{+} \to \tau^{+}\upsilon_{\tau}) = (0.72^{+0.27}_{-0.25} \pm 0.11) \times 10^{-4}$ with 3.0 σ significance[6].

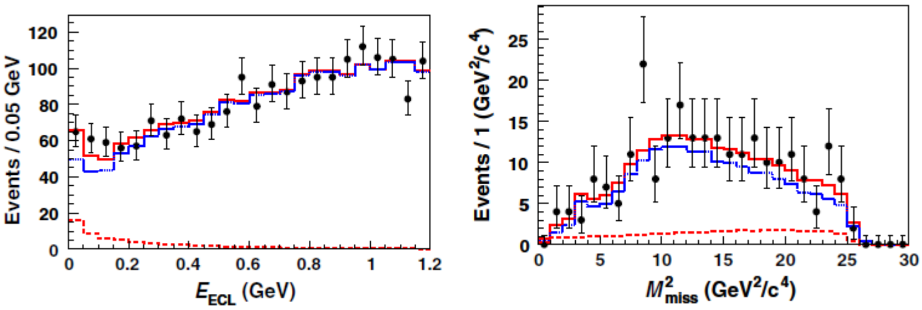


Figure 1. Distributions of E_{ECL} (left) and M^{2}_{miss} (right, for $E_{ECL} < 0.2$ GeV) combined for all the τ^{+} decays at Belle. The solid circles with error bars are data. The red dashed line is the signal and blue dotted line is the background component.

3.1.2 $B^{+} \to \tau^{+}\upsilon_{\tau}$ with semileptonic tag

After B_{tag} reconsturction, loose selection criteria is applied to maximize the efficiency, and use multivariate selection methods for well reconstructed B_{tag}. Cosine of the angle between the momentum of the B_{tag} meson and the $D^{(*)}l$ system should be have values between -1 and 1 if correctly reconstructed. $B^{+} \to \overline{D}^{0}\pi^{+}$, $B^{+} \to \overline{D}^{*0}(\overline{D}^{0}\pi^{0})l^{+}\nu_{l}$ double tagged sample is used to check the Data and MC difference with E_{ECL} and p^{*}_{sig} distribution. In τ → eνν sub-decay mode, converted photon backgrounds are removed from invariant mass conditions with other track. The signal extraction is obtained by unbinned two-dimensional fit for E_{ECL} and p^{*}_{sig} in the Figure 2. The obtained branching fraction is $\mathcal{B}(B^{+} \to \tau^{+}\upsilon_{\tau}) = (1.25 \pm 0.28 \pm 0.27) \times 10^{-4}$ with 3.8 σ significance[7].

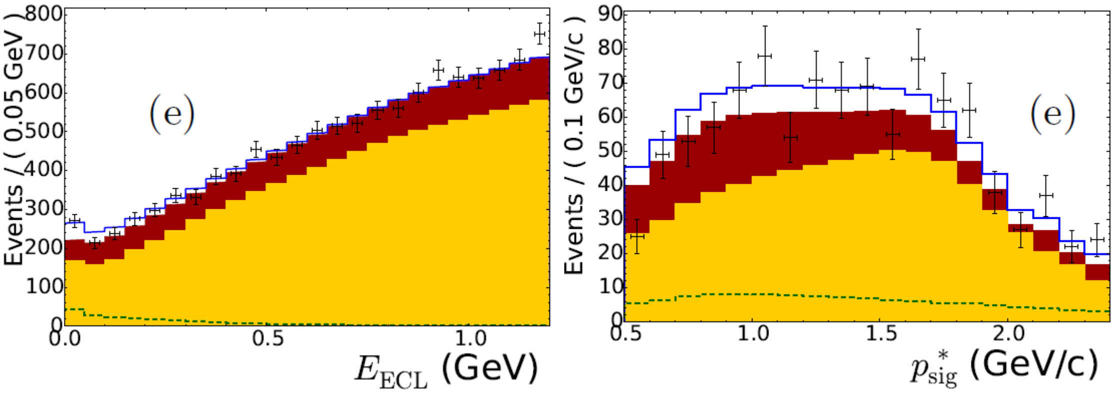


Figure 2. Distributions of E_{ECL} (left) and p^{*}_{sig} (right, for $E_{ECL} < 0.2$ GeV) combined for all the τ^{+} decays at Belle. Marker with error bar shows the data distribution. The blue solid line is the total fitted distribution. Blue dashed line is the signal component and orange (red) filled distribution is the $B\overline{B}$ (continuum) background.

3.2 $B^{+} \to l^{+}\upsilon_{l}$

The most stringent upper limit of $B^{+} \to \mu^{+}\upsilon_{\mu}$ ($\mathcal{B}(B^{+} \to \mu^{+}\upsilon_{\mu}) < 1.0 \times 10^{-6}$) is measured by untagged method by Babar[8]. The signal is extracted by two-dimensional fitting with m_{ES} and p_{FIT}, where is Fisher discriminant of signal lepton's momentum in the signal B rest frame and CM frame. The most stringent upper limit of $B^{+} \to e^{+}\upsilon_{e}$ ($\mathcal{B}(B^{+} \to e^{+}\upsilon_{e}) < 9.8 \times 10^{-7}$) is measured by unttaged method by Belle[9]. The signal is extracted with M_{bc} fit, where reconstructed B meson with all charged and neutral particles except for signal lepton candidate.
There are also $B^{+} \to l^{+}\upsilon_{l}$ results with tagged method.
At Babar, there are two results with semileptonic and hadronic tag.
In case of semileptonic tag, signal is extracted by E_{Extra}. Mesuared upper limits are order of 10^{-5}[10]. In hadronic tag, lepton momentum is fitted to extract the signal. Mesuared upper limits are $\mathcal{B}(B^{+} \to \mu^{+}\upsilon_{\mu}) < 5.6 \times 10^{-6}, \mathcal{B}(B^{+} \to e^{+}\upsilon_{e}) < 5.2 \times 10^{-6}$[11].
At Belle, there is result of hadronic tag. Signal is extracted by p^{B}_{l}, momentum of the signal lepton at signal B rest frame. Events with $E_{ECl} < 0.5$ GeV are rejected. Upper limits are calculated using Feldman-Cousins method[12]. No events are observed in the signal region ($2.6 < p^{B}_{l} < 2.7$ GeV) as shown in Figure 3. And obtained upper limits are $\mathcal{B}(B^{+} \to \mu^{+}\upsilon_{\mu}) < 2.7 \times 10^{-6}, \mathcal{B}(B^{+} \to e^{+}\upsilon_{e}) < 3.5 \times 10^{-6}$ [13], most stringent limits with hadronic tag.

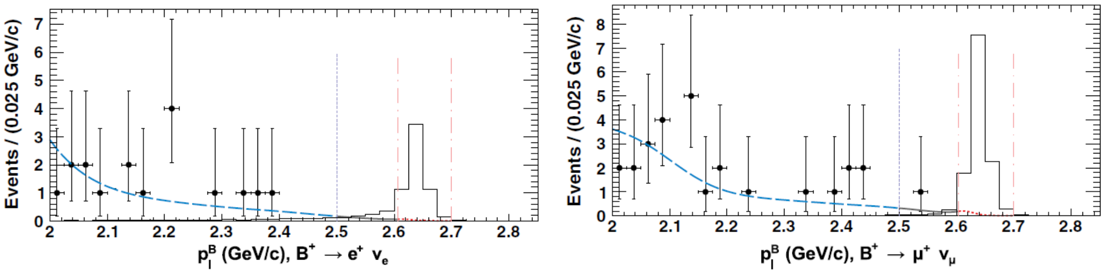
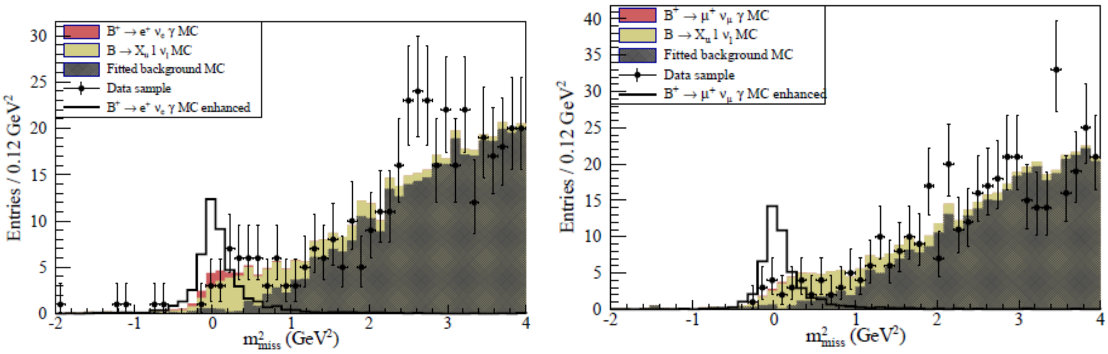


Figure 3. Distributions of p_l^B for $B^+ \to e^+\upsilon_e$(left) and $B^+ \to \mu^+\upsilon_\mu$ (right) at Belle. The points with error bars are the data. Solid histogrames are for the signal MC distributions which are scaled up arbitrary. Red dotted line shows signal region and blue dashed line is expected background.

3.3 $B^+ \to l^+\upsilon_l\gamma$

$B^+ \to l^+\upsilon_l\gamma$ decays are studied with hadronic tag only. At Babar, signal extraction is done using m_ν^2 by count the events. Obtained branching fractions are $\mathcal{B}(B^+ \to \mu^+\upsilon_\mu\gamma) < 17 \times 10^{-6}\mathcal{B}(B^+ \to e^+\upsilon_e\gamma) < 24 \times 10^{-6}\mathcal{B}(B^+ \to l^+\upsilon_l\gamma) < 15.6 \times 10^{-6}$ [14]. At Belle, two cases are considered by signal photon energy at the signal B rest frame E_γ^B ($E_\gamma^B >$ 1.0 GeV , $E_\gamma^B >$ 0.4 GeV). Signal extraction is done by using two variables. One is m_{mass}^2 and another is neural network output of from E_{ECL}, angle information of signal candidate lepton and photon, and many invariant mass with signal photon and any background photons to reject $B^+ \to l^+\nu_l\pi^0$ and $B^+ \to l^+\nu_l\eta$ background. The signal is obtained by extended unbinned maximum likelihood fit to the m_{mass}^2 distribution (Fig. 4) in six bins of the neural network output (Fig. 5). We obtained the most stringent upper limits. ($E_\gamma^B >$ 1.0 GeV)

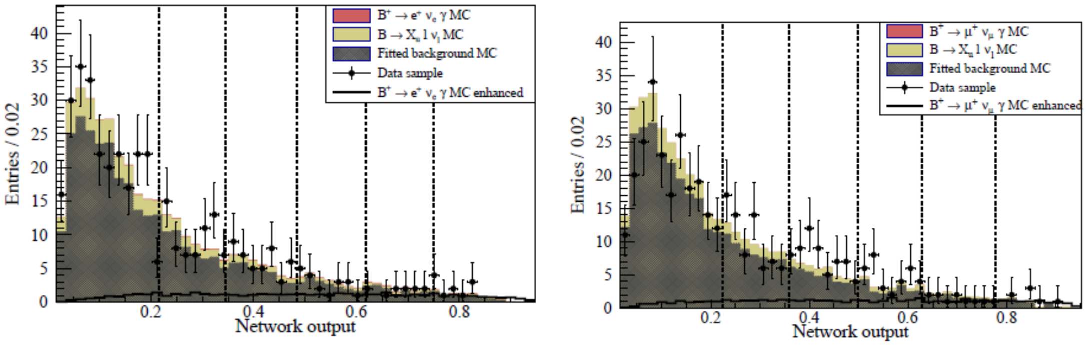
$$\mathcal{B}(B^+ \to \mu^+\upsilon_\mu\gamma) < 3.4 \times 10^{-6}$$
$$\mathcal{B}(B^+ \to e^+\upsilon_e\gamma) < 6.1 \times 10^{-6}$$
$$\mathcal{B}(B^+ \to l^+\upsilon_l\gamma) < 3.5 \times 10^{-6}[15]$$



(a) Electron channel

(b) Muon channel

Figure 4. Distributions of m_{miss}^2 at Belle where the enhanced signal corresponds to a branching fraction of 30×10^{-6}.



(a) Electron channel

(b) Muon channel

Figure 5. Network outputs used for m^2_{miss} binning, at Belle, where the bin boundaries are indicated by the dashed lines.

4. Conclusion

B-factories have studied purely leptonic and radiative leptonic decay with a goal of searching for new physics beyond the SM. Semileptonic tag $B^+ \to \tau^+ \upsilon_\tau$ searches at Belle has 3.8 σ significance and Belle combined branching fraction has 4.6 σ significance. Radiative decay searches at Belle gives most stringent upper limit of branching fraction. B-factory experiments have an advantage for these studies and these will remain important subjects in future experiments.

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