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$B^+ \to \tau^+\nu_\tau$ and $B \to K^{(*)}\nu\overline{\nu}$ at *BABAR* and SuperB

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1 Introduction

The $B^+ \to \tau^+\nu_\tau$ and $B \to K^{(*)}\nu\overline{\nu}$ decays are quite distinct from one another, the former a tree-level process and the latter only occurring via loop or box diagrams, and the theoretical motivations for measuring these decays are equally divergent. However, the experimental search for these two processes is similar, as both decays have final states with a single reconstructed particle and several neutrinos. Since $B^+ \to \tau^+\nu_\tau$ and $B \to K^{(*)}\nu\overline{\nu}$ cannot be fully reconstructed, the clean, hermetic environments of the B Factories provide sensitivity to these decays. During its lifetime, the *BABAR* experiment [1] collected 429 fb^{-1} of data at the $\Upsilon(4S)$ resonance, which corresponds to ~ 470 million $B\overline{B}$ pairs. The SuperB experiment [2], a next-generation B Factory, aims to produce $75\,\text{ab}^{-1}$ at the $\Upsilon(4S)$ resonance over a five-year period.[1]

The $\Upsilon(4S) \to B\overline{B}$ production at B Factories can be exploited by fully reconstructing one B meson (B_{tag}) in a number of hadronic final states in order to determine the signal B four-vector for improved resolution on the sighnal kinematics and the missing four-momentum. The "energy-substituted" mass of the B_{tag}, $m_{\text{ES}} \equiv \sqrt{E^2_{\text{beam}} - \vec{p}^{\,2}_{B_{\text{tag}}}}$, peaks at the nominal B mass for correctly reconstructed B_{tag} candidates, and produces a relatively flat distribution from combinatoric background. In both the $B^+ \to \tau^+\nu_\tau$ and $B \to K^{(*)}\nu\overline{\nu}$ searches described in this paper, the signal efficiency and peaking background, estimated from Monte Carlo (MC) modeling, are validated with data using this m_{ES} distribution. The combinatoric background is extrapolated directly from data in the m_{ES} sideband regions.

2 The $B^+ \to \tau^+\nu_\tau$ measurement

Within the Standard Model (SM), the leptonic decay $B^+ \to \tau^+\nu_\tau$ proceeds via an annihilation of b and u quarks into a virtual W^+ boson. Without QCD-based uncer-

[1]Following this conference, the SuperB experiment was canceled. A similar experiment Belle II [3] expects $50\,\text{ab}^{-1}$.

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tainties in the final state, leptonic decays can provide clean theoretical predictions of SM parameters like $|V_{ub}|$ and the B-meson decay constant f_B. Both these parameters dominate the SM uncertainty of the branching fraction

$$\mathcal{B}(B^+ \to \ell^+ \nu_\ell)_{\rm SM} = \frac{G_F^2 m_B}{8\pi} |V_{ub}|^2 f_B^2 \tau_B m_\ell^2 \left(1 - \frac{m_\ell^2}{m_b^2}\right)^2 \tag{1}$$

where the square of the lepton mass, m_ℓ^2, indicates a helicity suppression. Thus, while $\mathcal{B}(B^+ \to e^+\nu_e)$ and $\mathcal{B}(B^+ \to \mu^+\nu_\mu)$ [4] have been inaccessible at current B Factories, the SM predicts $\mathcal{B}(B^+ \to \tau^+\nu_\tau)$ to be on the order of 10^{-4}. This rate can be significantly enhanced or suppressed by the contribution of a charged Higgs boson in place of the W^+ boson. For example, in the Type-II two-Higgs doublet model (2HDM) [5], Eq. (1) is multiplied by an additional factor $\left(1 - \tan^2\beta \frac{m_B^2}{m_H^2}\right)^2$, where m_H is the mass of the H^+ and $\tan\beta$ is the ratio of the vacuum expectation values. Thus, measuring the $B^+ \to \tau^+\nu_\tau$ branching fraction can constrain the parameters of new physics models.

The recent search for $B^+ \to \tau^+\nu_\tau$ [6], using the full *BABAR* dataset, requires a reconstructed $B_{\rm tag}$ and exactly one track corresponding to a one-prong decay of the tau: $e\nu\overline{\nu}$, $\mu\nu\overline{\nu}$, $\pi^+\nu$, or $\rho\nu \to \pi^+\pi^0\nu$. Two event-shape variables are employed to suppress $e^+e^- \to q\overline{q}$ ($q = u, d, s, c$) backgrounds. In addition, the angle of the missing three-momentum ($\cos\theta_{\rm miss}$) and the momentum of the pion in the center-of-mass frame (p_π^*) are used in a two-variable likelihood ratio to reduce background in the $\tau \to \pi\nu$ channel. The $\tau \to \rho\nu$ channel uses a four-variable likelihood: $\cos\theta_{\rm miss}$, p_π^*, and the invariant masses of the π^0 and ρ candidates.

After reconstructing the $B_{\rm tag}$ and τ, the sum of the remaining energy in the detector ($E_{\rm extra}$) should be zero. However, mis-reconstructions and noise typically contribute to additional energy in the event. Using samples of fully-reconstructed "double-tagged" events, in which a second B is hadronically or semileptonically reconstructed opposite the $B_{\rm tag}$, the MC modeling of $E_{\rm extra}$ is validated with data.

The branching fraction is extracted using an unbinned maximum likelihood fit to $E_{\rm extra}$ in all τ-decay channels simultaneously. An excess at low $E_{\rm extra}$ is observed, as shown in Fig. 1, corresponding to an exclusion of the null hypothesis at 3.8σ (including systematic uncertainties). This search measures $\mathcal{B}(B^+ \to \tau^+\nu_\tau) = (1.83^{+0.53}_{-0.49} \pm 0.24) \times 10^{-4}$ where the uncertainties are statistical and systematic respectively. Combining this measurement with that of a previous *BABAR* semileptonic-tag measurement with an independent dataset [7] gives $\mathcal{B}(B^+ \to \tau^+\nu_\tau) = (1.79 \pm 0.48) \times 10^{-4}$.

These results are consistent with previous measurements by *BABAR*, all of which suggest tension with other SM measurements. Assuming $f_B = 189 \pm 4$ [8], and extracting $|V_{ub}|$ from either inclusive or exclusive decay measurements, Eq. (1) predicts $\mathcal{B}(B^+ \to \tau^+\nu_\tau)_{\rm SM} = (1.18 \pm 0.16) \times 10^{-4}$ or $(0.62 \pm 0.12) \times 10^{-4}$, respectively. Furthermore, the fit of other experimental values within the Unitarity Triangle expects

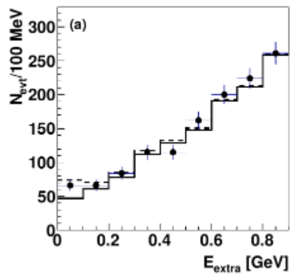

Figure 1: The final $E_{\rm extra}$ distribution in data (points) for all $B^+ \to \tau^+\nu_\tau$ channels fitted simultaneously. The best-fit distribution (dashed), which includes the signal excess, is overlaid on the expected background (solid).

$\mathcal{B}(B^+ \to \tau^+\nu_\tau)_{\rm fit} = (0.832 \pm 0.84) \times 10^{-4}$ [9].

To determine if this tension is evidence of new physics, the current world precision on $\mathcal{B}(B^+ \to \tau^+\nu_\tau)$ of $\sim 20\%$ must be reduced. Simulation studies show that with the $75\,\mathrm{ab}^{-1}$ of data expected from SuperB, the $\mathcal{B}(B^+ \to \tau^+\nu_\tau)$ precision should improve to about 3–4% [2]. The currently unobserved $B^+ \to \mu^+\nu_\mu$ decay should also be measurable with a 5–6% precision. In addition to its experimentally-clean two-body final state, $B^+ \to \mu^+\nu_\mu$ would give access to $\mathcal{B}(B^+ \to \mu^+\nu_\mu)/\mathcal{B}(B^+ \to \tau^+\nu_\tau)$, which is independent from the theoretical uncertainties of $f_B|V_{ub}|$.

3 The search for $B \to K^{(*)}\nu\overline{\nu}$

The flavor-changing neutral current decays $B \to K^{(*)}\nu\overline{\nu}$ are prohibited in the SM at tree-level, but can proceed via electroweak-penguin or box diagrams. These rare decays, predicted on the order of 10^{-6}, are sensitive to new physics scenarios which could contribute at the same order as the SM. These scenarios include non-standard Z couplings, new particles entering into the loops such as from Supersymmetric models, or invisible particles contributing to the final-state missing energy [10]. In addition to potentially significant branching-fraction enhancements, some new physics models suggest that the $B \to K^{(*)}\nu\overline{\nu}$ decay kinematics would also show modifications.

A recent (2012) search for $B \to K^{(*)}\nu\overline{\nu}$ uses the full *BABAR* dataset to select events with a reconstructed hadronic $B_{\rm tag}$ candidate, one additional $K^{(*)}$, and no extra tracks. This kaon is reconstructed in six signal channels: K^+, $K^0_S \to \pi^+\pi^-$, $K^{*+} \to K^+\pi^0$, $K^{*+} \to K^0_S\pi^+$, $K^{*0} \to K^+\pi^-$, and $K^{*0} \to K^0_S\pi^0$. Six event-shape variables are employed in a likelihood ratio to further suppress $e^+e^- \to q\overline{q}$ backgrounds, and $E_{\rm extra}$ is required to be less than a few hundred MeV.

The branching-fraction upper limits are obtained within the low $s_B \equiv q^2/(m_Bc)^2$ region, where q^2 is the invariant mass of the neutrino pair. This signal region, which corresponds to that of high-momentum kaons, has relatively little background, as shown in Fig. 2a. At 90% confidence level (CL), preliminary upper limits are determined to be $\mathcal{B}(B^+ \to K^+\nu\overline{\nu}) < 3.7 \times 10^{-5}$, $\mathcal{B}(B^0 \to K^0\nu\overline{\nu}) < 8.1 \times 10^{-5}$, $\mathcal{B}(B^+ \to K^{*+}\nu\overline{\nu}) < 11.6 \times 10^{-5}$, $\mathcal{B}(B^0 \to K^{*0}\nu\overline{\nu}) < 9.3 \times 10^{-5}$, withcd ba combined limits of $\mathcal{B}(B \to K\nu\overline{\nu}) < 3.2 \times 10^{-5}$, and $\mathcal{B}(B \to K^*\nu\overline{\nu}) < 7.9 \times 10^{-5}$. In addition, preliminary lower limits at 90% CL are set at $\mathcal{B}(B^+ \to K^+\nu\overline{\nu}) > 0.4 \times 10^{-5}$ and $\mathcal{B}(B \to K\nu\overline{\nu}) > 0.2 \times 10^{-5}$, although the significance above the null hypothesis is less than two. This search provides the most stringent upper limits for $B^0 \to K^0\nu\overline{\nu}$ and $B \to K^*\nu\overline{\nu}$ with the hadronic-tag reconstruction method.

Figure 2: (a) The final s_B distribution in data (points) for $B^+ \to K^+\nu\overline{\nu}$ events. The combinatoric (striped) plus m_{ES}-peaking (solid) background are overlaid with signal MC (dashed) normalized to 20×10^{-5} for visibility. The vertical line depicts the signal region. (b) The new physics constraints at 90% CL on η and ϵ. The $B \to K\nu\overline{\nu}$ (striped) and $B \to K^*\nu\overline{\nu}$ (shaded) excluded areas are determined from this $B \to K^{(*)}\nu\overline{\nu}$ analysis (solid lines) and from previous semileptonic-tag analyses (dashed lines). The dot shows the expected SM value.

Since some new physics models suggest enhancements in the kinematic spectrum at high s_B, model-independent sensitivity to new physics is achieved by removing the s_B requirement and determining partial branching fractions over the full phasespace. This search sets branching-fraction upper limits at 90% CL for several new physics models at an order of 10^{-5}. In addition, several new physics models could affect the Wilson coefficients, C_L^ν and C_R^ν, where the latter is zero in the SM. By redefining $C_{L,R}^\nu$ as [10]

$$\epsilon \equiv \frac{\sqrt{|C_L^\nu|^2 + |C_R^\nu|^2}}{|C_{L,\mathrm{SM}}^\nu|}\ , \quad \eta \equiv \frac{-\mathrm{Re}(C_L^\nu C_R^{\nu *})}{|C_L^\nu|^2 + |C_R^\nu|^2}\ , \tag{2}$$

one can combine the results of $B \to K\nu\overline{\nu}$ and $B \to K^*\nu\overline{\nu}$ to constrain new physics, as shown in Fig. 2b. The $B \to K\nu\overline{\nu}$ lower limits provide the first upper limits on η and first lower limits on ϵ. The excluded parameter-space is in agreement with the SM expectation of $\eta = 0$, $\epsilon = 1$.

The rare decays $B \to K^{(*)}\nu\overline{\nu}$ may be inaccessible at current B Factories, but they are expected to be measured at SuperB. Simulation studies show that $B \to K\nu\overline{\nu}$ may be observed at 3σ with about $10\,\mathrm{ab}^{-1}$, and $B \to K^{*}\nu\overline{\nu}$ around $50\,\mathrm{ab}^{-1}$ [11]. With $75\,\mathrm{ab}^{-1}$ and assuming SM values, the precision on the branching fraction measurements are expected to be 15–20%. In addition, the longitudinal polarization fraction of $B \to K^{*}\nu\overline{\nu}$ decays may be accessible around $75\,\mathrm{ab}^{-1}$, giving yet another handle on new physics constraints.

4 Conclusions

BABAR has recently measured $\mathcal{B}(B^+ \to \tau^+\nu_\tau)$ and obtained limits on $\mathcal{B}(B \to K^{(*)}\nu\overline{\nu})$ using hadronic-tag reconstruction of the recoiling B meson. The result $\mathcal{B}(B^+ \to \tau^+\nu_\tau) = (1.83^{+0.53}_{-0.49} \pm 0.24) \times 10^{-4}$ is consistent with previous *BABAR* measurements, although it is slightly above the SM expected value. The rare decays $B \to K^{(*)}\nu\overline{\nu}$ are not yet observed, but the new upper and lower limits are approaching the SM predictions. With the expected data from SuperB, the $B^+ \to \tau^+\nu_\tau$ tensions will likely be confirmed or excluded with improved precision, and $B \to K^{(*)}\nu\overline{\nu}$ and $B^+ \to \mu^+\nu_\mu$ decays are expected to be observed.

References

[1] B. Aubert *et al.* [BABAR Collaboration], Nucl. Instrum. Meth. A **479**, 1 (2002).

[2] M. Bona *et al.* [SuperB Collaboration], Pisa, Italy: INFN (2007) 453 p. `www.pi.infn.it/SuperB/?q=CDR` [arXiv:0709.0451 [hep-ex]].

[3] T. Abe [Belle II Collaboration], arXiv:1011.0352 [physics.ins-det].

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

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

[6] J. P. Lees *et al.* [BABAR Collaboration], submitted to Phys. Rev. D, arXiv:1207.0698 [hep-ex].

[7] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. D **81**, 051101 (2010).

[8] H. Na, C. J. Monahan, C. T. H. Davies, R. Horgan, G. P. Lepage and J. Shigemitsu, Phys. Rev. D **86**, 034506 (2012).

[9] J. Charles *et al.* [CKMfitter Group Collaboration], Eur. Phys. J. C **41**, 1 (2005) [hep-ph/0406184], Winter 2012 results from `http://ckmfitter.in2p3.fr`.

[10] W. Altmannshofer, A. J. Buras, D. M. Straub and M. Wick, JHEP **0904**, 022 (2009).

[11] B. O'Leary *et al.* [SuperB Collaboration], arXiv:1008.1541 [hep-ex].