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Results on Searches for New Physics at B Factories

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We summarize recent results on $B^+ \to \tau^+\nu_\tau$ setting constraints on the charged Higgs mass, discuss the CP puzzle in $B \to K\pi$ decays and present searches for a light neutral Higgs in radiative $\Upsilon(2S)$ and $\Upsilon(3S)$ decays.

1 Introduction

Rare decays are processes with branching fractions of $\mathcal{O}(10^{-4})$ or smaller. Typically, they arise if amplitudes of higher-order processes (penguin loops, box diagrams) become dominant because tree amplitudes are suppressed in the Standard Model (SM). Additional suppression comes from small CKM couplings and helicity conservation. Contributions of New Physics (NP) processes may become significant modifying the prediction with respect to those in the SM. Thus, rare decays provide an interesting hunting ground for NP searches that are complementary to direct searches at the LHC.

2 Measurement of $\mathcal{B}(B^+ \to \tau^+\nu_\tau)$

In the SM, $B^+ \to \tau^+\nu_\tau$[a] proceeds via W annihilation which is helicity-suppressed. The branching fraction involves the B decay constant (f_B), the CKM matrix element ($|V_{ub}|$), and the τ mass. For a recent lattice result of $\mathrm{f_B} = 195 \pm 11$ MeV [1] and $|V_{ub}| = (3.93 \pm 0.36) \times 10^{-3}$[2] the SM prediction yields $\mathcal{B}(B^+ \to \tau^+\nu_\tau) = (1.04 \pm 0.19 \pm 0.12) \times 10^{-4}$, where the uncertainties originate from the errors in $|V_{ub}|$ and f_B, respectively. In extensions of the SM, an additional contribution may arise from a charged Higgs boson modifying the branching fraction by an additional factor [3]

$$r_H = \big(1 - \frac{m_B^2}{m_H^2}\frac{\tan^2\beta}{1+\epsilon_0\tan\beta}\big)^2, \tag{1}$$

where m_H (m_B) is the mass of the charged Higgs boson (B^+ meson), $\epsilon_0 \simeq 0.01$ is an effective coupling [4] and $\tan\beta$ is the ratio of vacuum expectation values of the two Higgs doublets.

Both BABAR and Belle looked for $B^+ \to \tau^+\nu_\tau$ analyzing 467 Million and 657 million $B\bar{B}$ events, respectively. One B meson, called a "tag", is fully reconstructed in semileptonic $B \to D^0\ell\nu X$ or hadronic decays. In the recoil one looks for decays $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$, $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$, $\tau^+ \to \pi^+\bar{\nu}_\tau$ and $\tau^+ \to \rho^+\bar{\nu}_\tau$, thus selecting events with an isolated e^+, μ^+, π^+ or $\pi^+\pi^0$ in the recoil. For signal candidates the extra neutral energy in the event, $\mathrm{E_{extra}}$, is examined. This is the energy of all photons in the electromagnetic calorimeter that do not belong to the signal nor the reconstructed tag. For correctly reconstructed tags E_{extra} represents the summed noise in the calorimeter. Double semileptonic tags are used to cross check the simulation.

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[a]charge conjugation is implied unless otherwise stated

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The E_{extra} distribution measured in BABAR is shown in Figure 1. We extract signal in the region $\mathrm{E_{extra}} < 0.2$ GeV after extrapolating background from a sideband ($\mathrm{E_{extra}} > 0.6$ GeV). We see an excess of 89 ± 44 events. The total selection efficiency is $\epsilon = (1.18 \pm 0.1) \times 10^{-3}$. Including the yields of a previous analysis using hadronic tags we measure a 3.2σ significant branching fraction of $\mathcal{B}(B^+ \to \tau^+\nu_\tau) = (1.8 \pm 0.6_{stat} \pm 0.1_{sys}) \times 10^{-4}$ [5].

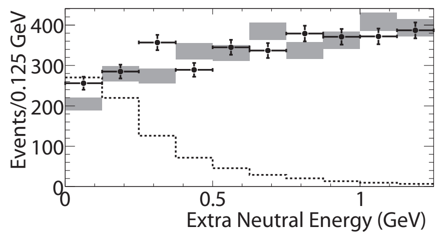

Figure 1: Distribution of extra neutral energy for semileptonic tags from BABAR showing data (points), expected background (shaded histogram) and expected signal (dotted line).

Belle sees an excess of 154^{+36+20}_{-35-22} events measuring a branching fraction of $\mathcal{B}(B^+ \to \tau^+\nu_\tau) = (1.65^{+0.38+0.35}_{-0.37-0.37}) \times 10^{-4}$ (3.8σ significance) [6]. This is in good agreement with $\mathcal{B}(B \to \tau\nu) = (1.79^{+0.56+0.46}_{-0.49-0.51}) \times 10^{-4}$ measured in hadronic tags using 449 million $B\bar{B}$ events [7].

Accounting for correlated systematic uncertainties the BABAR/Belle average is $\mathcal{B}(B^+ \to \tau^+\nu_\tau) = (1.73 \pm 0.37) \times 10^{-4}$ (4.6σ significance). Division by the SM branching fraction yields $r_H = 1.67 \pm 0.36 \pm 0.36$, where the first error gives the total experimental uncertainty and the second error accounts for uncertainties in f_B and $|V_{ub}|$.

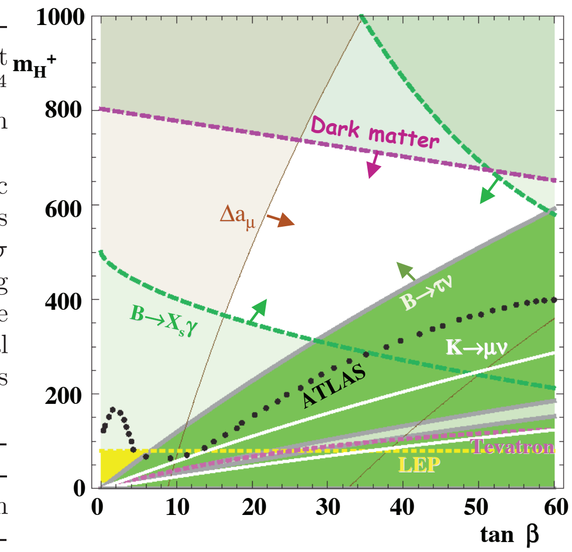

Figure 2: Exclusion regions at 95% $C.L.$ in the $m_H - \tan\beta$ plane from measurements of $\mathcal{B}(B^+ \to \tau^+\nu_\tau)$ (thick solid lines), $\mathcal{B}(K^+ \to \mu^+\nu_\mu)$ (light solid lines), $\mathcal{B}(B \to X_s\gamma)$ (lower an upper right thick dashed lines), dark matter searches (upper thick dashed line), Δa_μ (left and right thin solid lines), charged Higgs searches at LEP (thin light dotted line), charged Higgs searches at the Tevatron (thin dark dotted line) and the 5σ discovery curve in ATLAS for 30 fb^{-1} (thick dotted line).

From the measurement of r_H we determine 95% confidence level (C.L.) contours in $m_H - \tan\beta$ plane that are shown in Figure 2 for the Minimal Supersymmetric Standard Model (MSSM) with minimum flavor violation. In addition, we show 95% C.L. contours for $\mathcal{B}(K^+ \to \mu^+\nu_\mu)$ [2], $\mathcal{B}(B \to X_s\gamma)$ [2], Δa_μ (difference of measured anomalous magnetic moment of the muon and the SM prediction, $1.2 \times 10^{-9} < \Delta a_\mu < 4.6 \times 10^{-9}$) [9], dark matter searches ($0.079 < \Omega_{CDM}h^2 < 0.119$) [10], and Higgs searches at LEP and at the Tevatron [2] that are calculated for a heavy-squark scenario ($\mathrm{M_{\tilde{q}}} = 1.5$ TeV, $\mathrm{A_U} = -1$ TeV, $\mu = 0.5$ TeV and $\mathrm{M_{\tilde{\ell}}} = 0.4$ TeV) [11]. Note that $\mathcal{B}(B^+ \to \tau^+\nu_\tau)$ and $\mathcal{B}(K^+ \to \mu^+\nu_\mu)$ already exclude a large part of the $m_H - \tan\beta$ plane. The other constraints come from dark mater searches, Δa_μ and $\mathcal{B}(B \to X_S\gamma)$. The allowed region is the white area located in the center of the plot. The dotted curve shows the 5σ discovery curve expected in ATLAS for $30 fb^{-1}$ [12]. For other SUSY parameters, the allowed area typically shrinks [11].

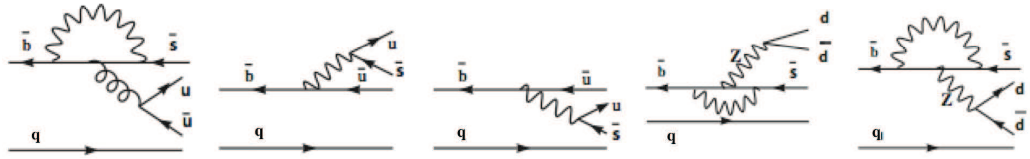

Figure 3: Lowest-order diagrams for $B \to K\pi$ decays, (from left to right) gluonic penguin, tree, color-suppressed tree, color-allowed EW penguin and color-suppressed EW penguin.

3 The CP Puzzle in $B \to K\pi$ Decays

The decays $B \to K\pi$ are dominated by gluonic penguin amplitudes with a t-quark in the loop ($P'_t \sim \mathcal{O}(1)$). Tree amplitudes (T') are suppressed by $\mathcal{O}(\lambda)$, while color-suppressed tree (C') and gluonic penguin amplitudes with a u-quark in the loop (P'_u) are suppressed by $\mathcal{O}(\lambda^2)$, where $\lambda = 0.22$. In addition, electroweak (EW) penguin (P'_{EW}) and color-suppressed EW penguin amplitudes (P'^{C}_{EW}) contribute at $\mathcal{O}(\lambda)$ and $\mathcal{O}(\lambda^2)$, respectively [13].

In $B^+ \to K^+\pi^0$ and $B^0 \to K^0\pi^0$ decays all processes shown in Figure 3 contribute, while in $B^0 \to K^+\pi^-$ and $B^+ \to K^0\pi^+$ decays the amplitudes P'_{EW} and C' are absent. Since P'_{EW} is at $\mathcal{O}(\lambda)$, branching fractions might differ substantially due to interference. The measured ratios of branching fractions corrected for isospin and different B^+ (τ_+) and B^0 (τ_0) lifetimes are close to one: $\frac{\mathcal{B}(B^0 \to K^+\pi^-)}{2\times\mathcal{B}(B^+ \to K^+\pi^0)} \frac{\tau_+}{\tau_0} = 0.81 \pm 0.05$ and $\frac{2\times\mathcal{B}(B^0 \to K^0\pi^0)}{\mathcal{B}(B^+ \to K^0\pi^+)} \frac{\tau_+}{\tau_0} = 0.91 \pm 0.07$. The largest deviation is less than 20%, indicating that contributions from P'_{EW} and C' are small.

Direct CP violation is another interesting observable. *BABAR* updated direct CP violation measurements for $B^0 \to K^+\pi^-$ with the full data set. As shown in Figure 4 we see a large CP asymmetry of $\mathcal{A}(K^+\pi^-) = -0.107 \pm 0.016^{+0.006}_{-0.004}$ [14]. This increases the world average (WA) to $\mathcal{A}(K^+\pi^-) = -0.098^{+0.012}_{-0.011}$ (8.1σ significant). For $B^+ \to K^+\pi^0$ the WA is $\mathcal{A}(K^+\pi^0) = 0.05 \pm 0.025$. Though consistent with zero at the 2.0σ level the difference in CP asymmetries between B^0 and B^+ decays is increased to $\Delta\mathcal{A}_{K\pi} = \mathcal{A}(K^+\pi^-) - \mathcal{A}(K^+\pi^0) = -0.148 \pm 0.028$. Such a large effect ($5.3\sigma$) is unexpected. The discrepancy

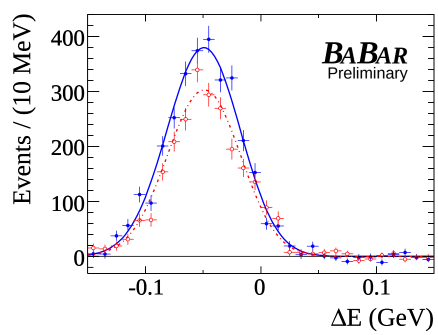

Figure 4: ΔE distributions for $B^0 \to K^+\pi^-$ (solid) and $\bar{B}^0 \to K^-\pi^+$ (dashed) decays.

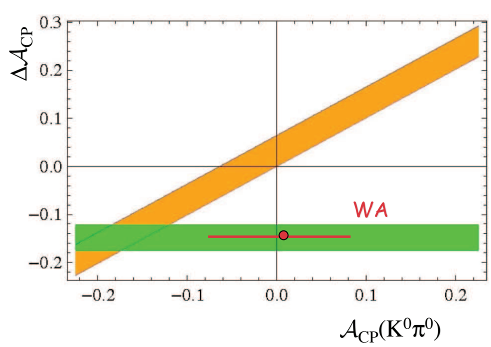

Figure 5: SM sum rule relating $\Delta\mathcal{A}_{K\pi}$ to $\mathcal{A}(K^0\pi^0)$ (diagonal band), WAs for $\Delta\mathcal{A}_{K\pi}$ (horizontal band) and $\mathcal{A}(K^0\pi^0)$ (point).

$\Delta\mathcal{A}_{K\pi}$ was attributed to either with a large C' [17] or large $P"_{EW}$ contribution [18]. An enhanced C' is due to a strong interaction effect, while an enhanced P'_{EW} may hint at NP in loop processes containing a charged Higgs boson or supersymmetric particles.

The measured value of $\mathcal{A}(K^0\pi^+) = 0.009 \pm 0.025$ is consistent with zero. For $B^0 \to K^0\pi^0$ both *BABAR* and Belle updated results. Observing $556 \pm 32 K^0_S\pi^0$ events in the full data set *BABAR* measures $\mathcal{A}(K^0\pi^0) = -0.13 \pm 0.13 \pm 0.03$. Belle measures $\mathcal{A}(K^0\pi^0) = 0.14 \pm 0.13 \pm 0.06$ by combining $657 \pm 37 K^0_S\pi^0$ and $285 \pm 77 K^0_L\pi^0$ events. The resulting WA of $\mathcal{A}(K^0\pi^0) = 0.01 \pm 0.10$ is in good agreement with $\mathcal{A}(K^0\pi^+)$, though errors are large.

In the SM a sum rule connects all four CP asymmetries [19, 20] by

$$\mathcal{A}(K^+\pi^-) + \mathcal{A}(K^0\pi^+)\frac{\mathcal{B}(K^0\pi^-)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_+}{\tau_0} = \mathcal{A}(K^+\pi^0)\frac{2\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_+}{\tau_0} + \mathcal{A}(K^0\pi^0)\frac{2\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}. \quad (2)$$

Figure 5 depicts the relation between $\Delta\mathcal{A}_{K\pi}$ and $\mathcal{A}(K^0\pi^0)$ graphically. If no NP is present, the $K^0\pi^0$ CP asymmetry is determined by the overlap region of the horizontal and diagonal bands yielding $\mathcal{A}(K^0\pi^0) = -0.151 \pm 0.043$. The present WA is consistent with this value at the 1.4σ level.

A recent study of the $K\pi$ system shows that all measurements are consistent with the SM at the 20% C.L. [21]. NP may contribute in gluonic penguin or electroweak penguin loops. For the first scenario one still expects $\mathcal{A}(K^0\pi^0) = -0.15$, while for the second scenario $\mathcal{A}(K^0\pi^0) = -0.03$. The precision of present data is not sufficient to distinguish between both scenarios. A factor of ten more data is required to settle the issue. Since LHCb cannot measure the $K^0\pi^0$ mode, a Super B-factory is needed to produce precise measurements [22].

4 Search for Neutral Light Higgs in Υ Decays

In the simplest extension of the Minimal Supersymmetric Standard Model (MSSM), called NMSSM, a CP -odd Higgs singlet A_S is introduced that mixes with the MSSM CP -odd state A_{MSSM} [23]. The physical state is $A^0 = A_S \sin\theta_A + A_{MSSM}\cos\theta_A$, where θ_A is the mixing angle. Searches at LEP imposed a lower bound of $|\cos\theta_A| \geq 0.04$ for $\tan\beta = 10$. For decays $A^0 \to \tau^+\tau^-$ the coupling is proportional to $\cos\theta_A \tan\beta$. Since the A^0 may be produced in radiative Υ decays with branching fractions predicted as large as few $\times 10^{-4}$, we searched in *BABAR* for $\Upsilon(3S) \to \gamma A^0$, $A^0 \to (\mu^+\mu^-, \tau^+\tau^-$, or invisible) using $(121.8 \pm 1.2) \times 10^6$ $\Upsilon(3S)$ decays and $\Upsilon(2S) \to \gamma A^0$, $A^0 \to \mu^+\mu^-$ using $(98.6 \pm 0.9) \times 10^6$ $\Upsilon(2S)$ decays [24].

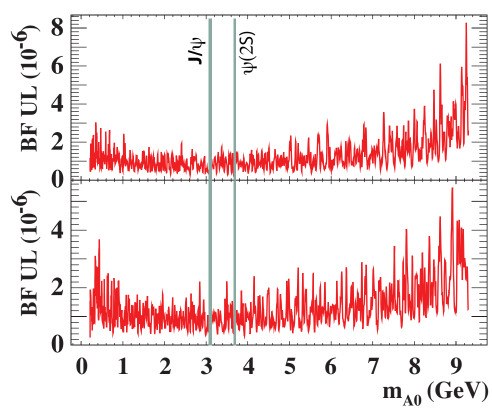

Figure 6: Branching fraction upper limits at 90% C.L. for $\Upsilon(2S) \to \gamma A^0$, $A^0 \to \mu^+\mu^-$ (top) and $\Upsilon(3S) \to \gamma A^0$, $A^0 \to \mu^+\mu^-$ (bottom).

We select events with a photon recoiling against two charged tracks with zero net charge or large missing energy. The latter topology covers the A^0 decay into a pair of lightest SUSY particles that escape detection. For the $\mu^+\mu^-$ decay, we require two identified muons for $m_{\mu\mu} < 1.05$ GeV to remove ρ^0 background.

We perform a kinematic fit at the $\Upsilon(2S)$, $\Upsilon(3S)$ and calculate the reduced mass $m_r = \sqrt{m_{\mu\mu} - 4m_\mu^2}$, for which continuum background from $e^+e^- \to \gamma\mu^+\mu^-$ is smooth near threshold. Fitting the $\mu^+\mu^-$ mass spectrum in 300 MeV bins we see no signal in the entire mass region from $2m_\mu$ to 9.3 GeV. Thus, we set branching fraction upper limits at 90% C.L. shown in Figure 6. The limits vary from $0.27(0.26) \times 10^{-6}$ to $5.5(8.3) \times 10^{-6}$ for $\Upsilon(3S)(\Upsilon(2S))$ decays.

In the search for $A^0 \to \tau^+\tau^-$, we only select e^+e^-, $\mu^+\mu^-$ and $e^\pm\mu^\mp$ decays in which both leptons are identified. We look for an excess in a narrow region in the E_γ spectrum. We observe no significant signal and set branching fraction upper limits at 90% C.L. shown in Figure 7. The upper limits vary from 15×10^{-6} to 160×10^{-6} being about an order of magnitude larger than those in the $\mu^+\mu^-$ mode. In the search for $A^0 \to$ invisible, event selection is optimized separately for photon energies $2.2 < \mathrm{E}_\gamma^* < 3.7$ GeV and $3.2 < \mathrm{E}_\gamma^* < 5.5$ GeV. In both regions an unbinned extended maximum likelihood fit is performed to the distribution of missing mass squared in steps of $\Delta \mathrm{m}_{\mathrm{A}^0} = 0.1$ GeV. We see no significant signal in the entire mass region $0 < \mathrm{m}_{\mathrm{A}^0} < 7.8$ GeV and set branching fraction upper limits at 90% C.L. shown in Figure 8, which range from 0.7×10^{-6} at 3 GeV to 31×10^{-6} at 7.6 GeV.

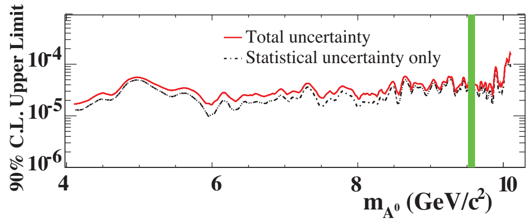

Figure 7: Branching fraction upper limits at 90% C.L. for $\Upsilon(3S) \to \gamma A^0$, $A^0 \to \tau^+\tau^-$

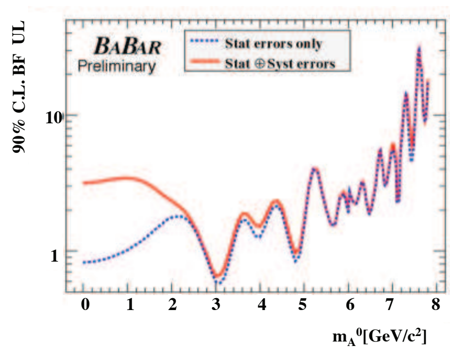

Figure 8: Branching fraction upper limits at 90% C.L. for $\Upsilon(3S) \to \gamma A^0$, $A^0 \to$ invisible.

5 Conclusion

The large samples of *BABAR* and Belle made it possible to study rare decays. Both experiments found evidence for $B^\pm \to \tau^\pm\nu_\tau$. The measured branching fraction is higher than the SM prediction placing stringent constraints on the mass of the charged Higgs boson. In the $B \to K\pi$ system, *CP* asymmetries between $K^+\pi^-$ and $K^+\pi^0$ modes differ unexpectedly by 5.3σ. The key issue is a precision measurement of $\mathcal{A}_{CP}(K^0\pi^0)$, since this will tell us if the SM holds up or NP is needed. Using radiative $\Upsilon(3S)$ decays we see no signal for a light neutral Higgs boson in the entire mass region. For a considerable improvement of these measurements a Super B-factory is needed.

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