Results on Searches for New Physics at B Factories

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We summarize recent results on $B^+ \to \tau^+\nu$, 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 $O(10^{-4})$ 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 $B(B^+ \to \tau^+\nu)$

In the SM, $B^+ \to \tau^+\nu$ 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 $\tau$ mass. For a recent lattice result of $f_B = 195 \pm 11$ MeV [1] and $|V_{ub}| = (3.93 \pm 0.36) \times 10^{-3}$ [2] the SM prediction yields $B(B^+ \to \tau^+\nu) = (1.04 \pm 0.19 \pm 0.12) \times 10^{-4}$, 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]

$$r_H = \left(1 - \frac{m_H^2}{m_B^2} \tan^2 \beta \right)^2,$$

where $m_H$ ($m_B$) is the mass of the charged Higgs boson ($B^+$ meson), $c_0 \simeq 0.01$ 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 $B^+ \to \tau^+\nu$, 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 $\tau^+ \to e^+\nu\bar{\nu}_e$, $\tau^+ \to \mu^+\nu\bar{\nu}_\mu$, $\tau^+ \to \pi^+\nu\bar{\nu}$, and $\tau^+ \to \rho^+\nu\bar{\nu}$, thus selecting events with an isolated $e^+, \mu^+, \pi^+$ or $\pi^+\pi^0$ in the recoil. For signal candidates the extra neutral energy in the event, $E_{\text{extra}}$, 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 $E_{\text{extra}}$ represents the summed noise in the calorimeter. Double semileptonic tags are used to cross check the simulation.

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acharge conjugation is implied unless otherwise stated.

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The $E_{\text{extra}}$ distribution measured in BaBar is shown in Figure 1. We extract signal in the region $E_{\text{extra}} < 0.2$ GeV after extrapolating background from a sideband ($E_{\text{extra}} > 0.6$ GeV). We see an excess of $89 \pm 44$ 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 $3.2\sigma$ significant branching fraction of $\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = (1.8 \pm 0.6_{\text{stat}} \pm 0.1_{\text{sys}}) \times 10^{-4}$ [5].

Belle sees an excess of $154_{-35}^{+36+20}/32$ events measuring a branching fraction of $\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = (1.65_{-0.37}^{+0.36} \pm 0.35) \times 10^{-4}$ (3.8$\sigma$ significance) [6]. This is in good agreement with $\mathcal{B}(B \to \tau \nu) = (1.79_{-0.49-0.51}^{+0.56+0.46}) \times 10^{-4}$ measured in hadronic tags using 449 million $B\bar{B}$ events [7].

Accounting for correlated systematic uncertainties the BaBar/Belle average is $\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = (1.73_{-0.37}^{+0.36}) \times 10^{-4}$ (4.6$\sigma$ 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 $|V_{ub}|$.

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], $\mathcal{B}(B \to X_{\gamma}\gamma)$ [2], $\Delta a_\mu$ (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 ($0.079 < \Omega_{\text{CDM}} h^2 < 0.119$) [10], and Higgs searches at LEP and at the Tevatron [2] that are calculated for a heavy-squark scenario ($M_q = 1.5$ TeV, $A_U = -1$ TeV, $\mu = 0.5$ TeV and $M_{\tilde{t}} = 0.4$ 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 matter searches, $\Delta a_\mu$ and $\mathcal{B}(B \to X_{\gamma}\gamma)$. The allowed region is the white area located in the center of the plot. The dotted curve shows the $5\sigma$ discovery curve expected in ATLAS for $30 \text{ fb}^{-1}$ (thick dotted line). For other SUSY parameters, the allowed area typically shrinks [11].
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 ($P_t' \sim O(1)$). Tree amplitudes ($T'$) are suppressed by $O(\lambda)$, while color-suppressed tree ($C'$) and gluonic penguin amplitudes with a $u$-quark in the loop ($P_t')$ are suppressed by $O(\lambda^2)$, where $\lambda = 0.22$. In addition, electroweak (EW) penguin ($P_{EW}'$) and color-suppressed EW penguin amplitudes ($P_{EW}^C$) contribute at $O(\lambda)$ and $O(\lambda^2)$, respectively.

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 $O(\lambda)$, branching fractions might differ substantially due to interference. The measured ratios of branching fractions corrected for isospin and different $B^+$ ($\tau_+$) and $B^0$ ($\tau_0$) lifetimes are close to one: $\frac{\mathcal{B}(B^0 \to K^+\pi^-)}{\mathcal{B}(B^+ \to K^0\pi^+)} \tau_0 = 0.81 \pm 0.05$ and $\frac{2\times\mathcal{B}(B^0 \to K^0\pi^0)}{\mathcal{B}(B^+ \to K^+\pi^+)} \tau_0 = 0.91 \pm 0.07$. 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 $\mathcal{A}(K^+\pi^-) = -0.107 \pm 0.016^{+0.006}_{-0.004}$ [4]. This increases the world average (WA) to $\mathcal{A}(K^+\pi^-) = -0.098^{+0.012}_{-0.011} (8.1\sigma$ 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 2.0$\sigma$ 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

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![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.](image)

![Figure 4: $\Delta E$ distributions for $B^0 \to K^+\pi^-$ (solid) and $B^0 \to K^-\pi^+$ (dashed) decays.](image)

![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).](image)
\(\Delta A_{K\pi}\) was attributed to either with a large \(C'\) \cite{17} or large \(P''_{EW}\) contribution \cite{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 \(A(K^0\pi^0) = 0.009 \pm 0.025\) is consistent with zero. For \(B^0 \rightarrow K^0\pi^0\) both \(B\bar{A}B\bar{A}\) and Belle updated results. Observing \(556 \pm 32 K_S^0\pi^0\) events in the full data set \(B\bar{A}B\bar{A}\) measures \(A(K^0\pi^0) = -0.13 \pm 0.13 \pm 0.03\). Belle measures \(A(K^0\pi^0) = 0.14 \pm 0.13 \pm 0.06\) by combining \(657 \pm 37 K_S^0\pi^0\) and \(285 \pm 77 K_L^0\pi^0\) events. The resulting WA of \(A(K^0\pi^0) = 0.01 \pm 0.10\) is in good agreement with \(A(K^0\pi^0)\), though errors are large.

In the SM a sum rule connects all four \(C\bar{P}\) asymmetries \cite{19}\cite{20} by

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

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

A recent study of the \(K\pi\) system shows that all measurements are consistent with the SM at the 20\% C.L. \cite{21}. NP may contribute in gluonic penguin or electroweak penguin loops. For the first scenario one still expects \(A(K^0\pi^0) = -0.15\), while for the second scenario \(A(K^0\pi^0) = -0.03\). 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 \cite{22}.

4 Search for Neutral Light Higgs in \(\Upsilon\) Decays

In the simplest extension of the Minimal Supersymmetric Standard Model (MSSM), called NMSSM, a \(C\bar{P}\)-odd Higgs singlet \(A_S\) is introduced that mixes with the MSSM \(C\bar{P}\)-odd state \(A_{MSSM}\) \cite{23}. The physical state is \(A^0 = A_S \sin \theta_A + A_{MSSM} \cos \theta_A\), where \(\theta_A\) is the mixing angle. Searches at LEP imposed a lower bound of \(|\cos \theta_A| > 0.04\) for \(\tan \beta = 10\). For decays \(A^0 \rightarrow \tau^+\tau^-\) the coupling is proportional to \(\cos \theta_A \tan \beta\).

Since the \(A^0\) may be produced in radiative \(\Upsilon\) decays with branching fractions predicted as large as few \(\times 10^{-4}\), we searched for \(\Upsilon(3S) \rightarrow \gamma A^0\), \(A^0 \rightarrow \mu^+\mu^-\) (or invisible) using \((121.8 \pm 1.2) \times 10^6\) \(\Upsilon(3S)\) decays and \(\Upsilon(2S) \rightarrow \gamma A^0\), \(A^0 \rightarrow \mu^+\mu^-\) using \((98.6 \pm 0.9) \times 10^6\) \(\Upsilon(2S)\) decays \cite{24}.

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 \(\rho^0\) 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 $e^+e^- \rightarrow \gamma\mu^+\mu^-$ 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 $A^0 \rightarrow \tau^+\tau^-$, 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 $E_\gamma$ 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 $15 \times 10^{-6}$ to $160 \times 10^{-6}$ being about an order of magnitude larger than those in the $\mu^+\mu^-$ mode. In the search for $A^0 \rightarrow \text{invisible}$, event selection is optimized separately for photon energies $2 < E_\gamma^* < 3.7$ GeV and $2 < E_\gamma^* < 5.5$ GeV. In both regions an unbinned extended maximum likelihood fit is performed to the distribution of missing mass squared in steps of $\Delta m_{A^0} = 0.1$ GeV. We see no significant signal in the entire mass region $0 < m_{A^0} < 7.8$ GeV and set branching fraction upper limits at 90\% C.L. shown in Figure 8 which range from $0.7 \times 10^{-6}$ at 3 GeV to $31 \times 10^{-6}$ at 7.6 GeV.

5 Conclusion

The large samples of BaBar and Belle made it possible to study rare decays. Both experiments found evidence for $B^{\pm} \rightarrow \tau^\pm\nu_\tau$. The measured branching fraction is higher than the SM prediction placing stringent constraints on the mass of the charged Higgs boson. In the $B \rightarrow K\pi$ system, $C_P$ asymmetries between $K^+\pi^-$ and $K^+\pi^0$ modes differ unexpectedly by $5.3\sigma$. The key issue is a precision measurement of $A_{CP}(K^0\pi^0)$, 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.

References


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