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Indirect Charged Higgs Constraints from BABAR

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The high-statistics data samples from the *BABAR* and Belle *B*-Factory experiments provide stringent constraints on charged Higgs bosons within the context of specific New Physics models. These constraints are obtained by comparing Standard Model predictions with experimental observations in rare B decays with potential sensitivity to contributions mediated by a virtual $H^{\pm}$ in tree or loop diagrams. Recent experimental results on the decays $B^{+} \to \mu^{+}\nu$, $B^{+} \to \tau^{+}\nu$ and inclusive $B \to X_{s}\gamma$ are described and the implications of these measurements for charged Higgs bosons is discussed.

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1. Introduction

High statistics data samples obtained from the SLAC and KEK B-Factories can be used to provide indirect constraints on a variety of new physics (NP) scenarios by looking for deviations from Standard Model (SM) predictions of various observables. Such deviations could arise from additional non-SM tree or loop-level processes containing massive virtual particles at scales well beyond the centre-of-mass energy of the B-Factory colliders. For a process to be sensitive to NP generally requires that the NP is comparable in size to the SM contribution, thus sensitive processes are usually "rare" decays which are suppressed in the SM either because there exists no tree-level SM process, or because the tree-level process is suppressed by a symmetry or conservation principle. In the present work, I will focus on recent experimental determinations of the inclusive $B \to X_s \gamma$ branching fraction and searches for the leptonic decays $B^+ \to \ell^+ \nu_\ell$ and the charged Higgs constraints that can be derived from them.

2. The B Factories and Experimental Methodology

The two asymmetric B-Factory experiments, *BABAR* at PEP-II and Belle at KEK have collected data at and around the $\Upsilon(4S)$ resonance since 1999. *BABAR* completed its data taking phase in 2008 with a total data sample corresponding to an integrated luminosity of 433 fb^{-1} at the $\Upsilon(4S)$, or roughly 500 million $\Upsilon(4S) \to B\overline{B}$ events. Belle continues to record data, but has recently reported analysis results based on samples containing approximately 650 million $B\overline{B}$ pairs. In both cases, the potential to constrain possible NP contributions in rare B_d decay modes results from the availability of high statistics data samples combined with the extremely clean experimental environment provided by e^+e^- operations.

The $B^+ \to \ell^+ \nu_\ell$ and inclusive $B \to X_s \gamma$ (where X_s represents any hadronic system containing a strange quark) analyses are conceptually quite different, but they share the common feature that they lack kinematic constraints which can be used to suppress backgrounds. In the case of $B^+ \to \ell^+ \nu_\ell$ (particularly for $\tau^+ \nu_\tau$), the presence of missing energy due to neutrinos in the final state make this search very challenging. For $B \to X_s \gamma$, any selection cuts applied to the X_s system potentially introduces systematic uncertainties due to the modeling of the X_s system. Several recent *BABAR* and Belle analyses have utilized a combination of "tag B" methods, which rely on the exclusive reconstruction of one of the two B_d mesons produced in $\Upsilon(4S)$ events, followed by a search for the signal decay ($B^+ \to \ell^+ \nu_\ell$ or $B \to X_s \gamma$) from among the remaining particles which are identified in these events. The advantages of this method are that non-$\Upsilon(4S)$ ("continuum") backgrounds are strongly suppressed, the resolution of various kinematic variables (e.g. missing energy) is improved, and that the signal decay should account for all remaining particles in the event. The disadvantage of this method is the low efficiency for the tag B reconstruction, which is at the level of a few parts per mille. Two techniques have been used by *BABAR*, and more recently by Belle, based on fully hadronic and semileptonic B decays. In the *BABAR* analyses, the reconstruction procedure begins with the identification of a "seed" D or D^* candidate which is obtained by combining charged and neutral pions and kaons which yield invariant mass combinations consistent with a $D^{(*)}$ in a limited set of clean decay modes. Good $D^{(*)}$ candidates are then combined with either a high momentum lepton (yielding a set of semileptonic tags), or with additional charged and neutral pions and kaons (yielding a purely hadronic tag sample) until the 4-vector of the resulting candidate is within a few hundred MeV of the expected energy of a B produced from a $\Upsilon(4S) \to B\overline{B}$ decay. For the hadronic tags, the 4-vector of the B candidate is fully determined, thus the invariant mass distribution can be used both to determine the tag yield and to estimate the combinatorial background. In practice, the mass resolution can be improved by constraining the energy component of the (CM frame) 4-vector, E, to the nominal B energy, $E_{CM}/2$, thus we define the two variables $\Delta E = E_{CM}/2 - E$ and the "energy-substituted mass" $m_{ES} = \sqrt{(E_{CM}/2)^2 - p_B^2}$, where p_B is the magnitude of the reconstructed B candidate momentum in the CM frame. The semileptonic tag reconstruction lacks this constraint, but instead exploits the fact that

$$\cos\theta_{B-D^0\ell} = \frac{2E_B E_{D^0\ell} - m_B^2 - m_{D^0\ell}^2}{2p_B p_{D^0\ell}} \tag{2.1}$$

(where the subscripts $D^0\ell$ and B represent the reconstructed D plus lepton combination, and the expected B meson) is the cosine of the angle between the B and $D^0\ell$ 4-vectors for a correctly reconstructed candidate. If the $D^0\ell$ candidate is actually a combinatorial background, then Equation 2.1 is violated and $\cos\theta_{B-D^0\ell}$ can take values outside of the range $[-1,1]$.

The hadronic tag reconstruction method has now been used by BABAR in searches for $B^+ \to \tau^+\nu$ [1], $B^+ \to \mu^+\nu$ and $B^+ \to e^+\nu$ [2], and for the measurement of $B \to X_s\gamma$ [3] and by Belle for $B^+ \to \tau^+\nu$ [4]. The semileptonic tag method has been used by both BABAR [5] and Belle [6] for $B^+ \to \tau^+\nu$. Because the $B^+ \to \mu^+\nu$ and $B^+ \to e^+\nu$ modes are two-body decays with only a single unobserved neutrino, the most stringent bounds on these modes currently are obtained from searches which do not use tag reconstruction. Similarly, "semi-inclusive" $B \to X_s\gamma$ analyses currently yield the most precise branching fraction [7] measurements. This situation may change in the relatively near future though as untagged analyses become limited by systematics/backgrounds and statistically-limited tagged analyses benefit from increasing data samples.

3. Leptonic B decays

Leptonic and semileptonic decays of B_d mesons occur in the SM via W-mediated tree level processes. In the case of semileptonic decays, the NP sensitivity is generally limited by high SM branching fractions and significant form factor uncertainties which tend to mask possible NP contributions. The exception is $B \to D^{(*)}\tau^+\nu_\tau$, which shows promise both from both the theoretical and experimental sides [8], but which is beyond the scope of the this work. The most stringent bounds currently arise from purely leptonic decays, $B^+ \to \ell^+\nu_\ell$. These are cleanly calculable in the SM as the hadronic matrix element is just f_B, the B_d meson decay constant. The SM branching fraction is given by

$$\mathscr{B}(B^+ \to \ell^+\nu_\ell) = \frac{G_f}{8\pi}|V_{ub}|^2 f_B^2 m_B m_\ell^2 \tau_B \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 \tag{3.1}$$

where G_f is the Fermi constant, V_{ub} is the CKM matrix element and τ_B and m_B are the B_d lifetime and mass respectively. The last term represents a phase space factor, which is close to unity for all three lepton species $\ell = e, \mu, \tau$, hence the three leptonic branching fractions differ primarily due to the helicity suppression factor m_ℓ^2, resulting in a suppression of the $\mu\nu$ ($e\nu$) final state by a factor of 200 (1×10^7) compared with the $\tau\nu$ mode.

In the generic Two Higgs Doublet Model (2HDM), sensitivity to charged Higgs bosons arises through a tree-level process in which the $H^\pm$ replaces the $W^\pm$ in the SM diagram [9]. Adding the charged Higgs contribution modifies Equation 3.1 by a multiplicative factor r_{H^+} given by

$$r_{H^+} = \left(1 - \frac{m_B^2}{m_{H^+}^2}\tan^2\beta\right)^2 \qquad (3.2)$$

where $\tan\beta$ is the ratio of the vacuum expectation values of the two Higgs doublets, and m_H^+ is the charged Higgs boson mass. It is notable that this expression does not contain a dependence on m_ℓ as one might naïvely expect from Higgs couplings. This can be understood from the helicity suppression of Equation 3.1: the $\tau^+\nu$ mode has a larger absolute $H^\pm$ contribution than the $\mu^+\nu$ mode, but both yield the same relative modification of the SM rate. This has two consequences. Firstly, the ratio of measured branching fractions for the $\tau^+\nu$ and $\mu^+\nu$ modes does not yield information regarding the charged Higgs[1], hence bounds based on Equations 3.1 and 3.2 need to rely on independent determinations of $|V_{ub}|$ and f_B. Perhaps surprisingly, this turns out to be a significant issue for the extraction of charged Higgs bounds. Secondly, determination of the branching fraction for any of the three leptonic modes with a given relative precision yields an equivalent charged Higgs constraint. This is important to point out since much of the recent focus has been on the $B^+\to\tau^+\nu$ mode, in spite of the fact that recent $B^+\to\mu^+\nu$ experimental bounds have been within about a factor of two of the SM value.

3.1 $B^+\to\mu^+\nu$

BABAR has previously published the results of searches for $B^+\to\mu^+\nu$ both using a method based on exclusive hadronic tag reconstruction [2] as well as using an un-tagged "inclusive" approach [11]. Recently, *BABAR* released a preliminary result based on the full data statistics using the un-tagged method [12]. Since $B^+\to\mu^+\nu$ is a two-body decay, the daughter μ^+ is mono-energetic in the B^+ rest frame, which differs by only a few hundred MeV from the CM frame. The B^+ frame can be inferred by requiring that the signal B direction is opposite that of a 4-vector sum of all particles in the event excluding the signal μ candidate. Substantial background suppression is also obtained by requiring that the 4-vector sum is consistent with that of a B meson, i.e. that it has ΔE and m_{ES} compatible with 0 and 5.27 GeV respectively. Due to detector non-hermiticity and the presence of spurious detector signals from beam backgrounds etc., the ΔE and m_{ES} resolution is quite poor using this method and so, consequently, is the B-frame μ momentum resolution. With the current B factory data samples these analyses predict a handful of signal events, assuming the SM rate for $B^+\to\mu^+\nu$, above backgrounds of typically tens of events. Hence the sensitivity of these searches is limited essentially by the fit of a peaking signal distribution above a non-peaking background and thus just scales with the squareroot of the background statistics. *BABAR* reports a preliminary limit of $B(B^+\to\mu^+\nu) < 1.3\times10^{-6}$ at 90% confidence and Belle has published a comparable limit [13] of $B(B^+\to\mu^+\nu) < 1.7\times10^{-6}$.

[1]The ratio of leptonic branching fractions, however, has been shown to be sensitive to lepton flavour violating couplings [10]

3.2 $B^+ \to \tau^+ \nu$

$B^+ \to \tau^+ \nu$ is experimentally much more difficult than $B^+ \to \mu^+ \nu$ due to the existence of multiple τ decay final states, the presence of multiple neutrinos and the fact that the kinematics of the observable final state particles do not provide particularly powerful background suppression. *BABAR* and Belle have now both reported results from searches for $B^+ \to \tau^+ \nu$ utilizing both the hadronic and semileptonic tag methods. Event selection proceeds by first reconstructing a B tag, and then requiring that there is only exactly one or three additional charged tracks in the event. Events with three tracks are interpreted as possible $\tau^+ \to a_1^+ \overline{\nu}_\tau$ candidates, while events with exactly one charged track are considered to be $\tau^+ \to e^+ \nu_e \overline{\nu}_\tau$, $\tau^+ \to \mu^+ \nu_\mu \overline{\nu}_\tau$, $\tau^+ \to \pi^+ \overline{\nu}_\tau$ or $\tau^+ \to \rho^+ \overline{\nu}_\tau$ depending on the particle identification status of the track. ρ candidates are obtained by combining π tracks with good $\pi^0 \to \gamma\gamma$ candidates formed from calorimeter clusters. If the combination falls within a window around the nominal ρ invariant mass, the event is considered to be $\tau^+ \to \rho^+ \overline{\nu}_\tau$. If no such combination exists, then the event is classified as $\tau^+ \to \pi^+ \overline{\nu}_\tau$. Once the event has been classified, all particles in the event have ostensibly been accounted for. Backgrounds can therefore be substantially suppressed by constraining the multiplicity and energy of any additional neutral calorimeter clusters in the event. However, in practice, even $B^+ \to \tau^+ \nu$ signal events frequently possess one or more additional low-energy clusters originating from hadronic split-offs, beam related backgrounds etc., hence the presence of additional clusters is characterized by the total amount of calorimeter energy, E_{extra}, which is not directly attributable to either the tag B or the $B^+ \to \tau^+ \nu$ signal candidate daughters. For signal events, E_{extra} peaks below a few hundred MeV. The most challenging experimental task is to understand this distribution, since many contributions to this quantity origniate from sources which are typically poorly modeled in Monte Carlo simulations. Mis-modeling can easily change the signal efficiency by tens of percent and, more importantly, potentially create signal-like peaking structures in the background distribution.

The $B^+ \to \tau^+ \nu$ branching fraction is obtained from the combination of several different τ decay modes - different analyses have chosen to include or exclude particular hadronic decay modes, but in practice the lowest backgrounds and hence strongest contributions to the $B^+ \to \tau^+ \nu$ result are obtained from the leptonic decay modes. It is notable however that polarization of the τ favours the production of low momentum leptons in the $\tau^+ \to \ell^+ \nu_\ell \overline{\nu}_\tau$ channels, hence particle identification performance can be an issue for these channels.

BABAR has published statistically independent results using the hadronic [1] and semileptonic [5] tag reconstruction methods based on 383×10^6 $B\overline{B}$ events and yielding branching fractions of $B(B^+ \to \tau^+ \nu) = (1.8^{+0.9}_{-0.8} \pm 0.4 \pm 0.2) \times 10^{-4}$ and $B(B^+ \to \tau^+ \nu) = (0.9 \pm 0.6 \pm 0.1) \times 10^{-4}$ respectively. The combination of these two results yields $B(B^+ \to \tau^+ \nu) = (1.2 \pm 0.4(\text{stat}) \pm 0.4(\text{syst})) \times 10^{-4}$, with a signal significance of 2.6σ from zero. Belle has recently reported a preliminary result [6] of $B(B^+ \to \tau^+ \nu) = (1.65^{+0.38+35}_{-0.37-37}) \times 10^{-4}$ using the semileptonic tag approach and had previously published a result [4] of $B(B^+ \to \tau^+ \nu) = (1.79^{+0.56+49}_{-0.46-51}) \times 10^{-4}$. A naïve combination of the *BABAR* and Belle results yields $B(B^+ \to \tau^+ \nu) = (1.51 \pm 0.33) \times 10^{-4}$, with a significance which is very close to 5σ.

Determination of r_{H^+} relies not only on the measured branching fraction, but also on the value of $|V_{ub}|$ and f_B. The fact that $|V_{ub}|$ determinations from B semileptonic decays differ by about 1.5σ from the value predicted by overall fits to the B_d unitarity triangle [15], combined with the existence of discrepancies in leptonic decays of charmed pseudoscalar mesons [16], make is unclear as to the best choice for $|V_{ub}|$ and f_B. In any case, it is clear that the uncertainties on r_{H^+} resulting from the SM prediction for $B(B^+ \to \tau^+\nu)$ is comparable in size to the current experimental uncertainty on the branching fraction.

Since the H^+ interferes destructively with the SM W^+, the H^+ contribution suppresses the $B^+ \to \ell^+\nu_\ell$ branching fractions compared with the SM expectation unless the H^+ contribution is very large. The large 2HDM charged Higgs exclusion region obtained from $B^+ \to \tau^+\nu$ and in particular the high-mass region, is therefore largely attributable to the fact that the current $B^+ \to \tau^+\nu$ branching fraction central value is somewhat high compared with the SM expectation. Taken at face value this would imply the existence of a charged Higgs with $\tan\beta/m_{H^+} \sim 0.28$, however this value is disfavoured based on other indirect (and direct, for low $\tan\beta$) measurements [14].

It is sometimes commented that the indirect flavour bounds on charged Higgs can be disregarded because they are model dependent, however, in the case of leptonic pseudoscalar meson decays, this is not really a problem. For example, in [17], the authors consider the MSSM with minimal flavour violation and conclude that equation 3.2 is modified to

$$r_{H^+} = \left(1 - \frac{m_B^2}{m_{H^+}^2}\frac{\tan^2\beta}{1+\varepsilon_0\tan\beta}\right)^2 \tag{3.3}$$

where ε_0 arises from non-holomorphic corrections to down-type Yukawa couplings. $\varepsilon_0\tan\beta$ can be of order unity for very large $\tan\beta$. This obviously modifies the $m_{H^+} - \tan\beta$ exclusion region somewhat compared with the generic 2HDM, but much less so than the effect due to the choice of $|V_{ub}| \cdot f_B$ as discussed above.

4. $B \to X_s\gamma$

$b \to s\gamma$ transitions are radiative flavour changing neutral current (FCNC) processes and hence are forbidden at tree level in the SM. They do however occur via one-loop diagrams containing a virtual top quark and $W^{\pm}$. NP can also enter at one-loop level and in particular, a charged Higgs boson can be substituted for the $W^{\pm}$ in the SM diagram, resulting in a predicted enhancement in the branching fraction which depends on m_{H^+}, but is relative independent of $\tan\beta$. In the generic 2HDM, this yields the potential for a stringent constraint. However, in the context of SUSY models additional NP contributions, such as squark-chargino loops, can potentially either further enhance or suppress the observed $b \to s\gamma$ rate thus clouding the interpretation of any experimental measurement. In the worst case, these contributions could exactly cancel the $H^{\pm}$ enhancement, resulting in an experimental determination which is indistinguishable from the SM, but in general any bounds in the $m_{H^+} - \tan\beta$ plane from $B \to X_s\gamma$ are very model-dependent. The interpretation of current experimental bounds within the context of specific NP models is discussed in detail in [18].

The potential NP sensitivity is also limited by hadronic uncertainties the the SM prediction. In general, the inclusive $b \to s\gamma$ (i.e. $B \to X_s\gamma$) branching fraction can be computed more reliably than specific exclusive $b \to s\gamma$ modes (assuming quark-hadron duality holds). The opposite is true experimentally: the fully inclusive measurement is extremely difficult. Recent calculations of NNLO QCD corrections [19] have substantially reduced the theoretical uncertainty on the inclusive branching fraction prediction while also shifting the central value downward by approximately 1σ.

The inclusive branching fraction is predicted to be in the range $(3.0-3.5)\times 10^{-4}$ for $E_\gamma > 1.6$ GeV, with uncertainties that vary from 7% to 14%.

On the experimental side, the inclusive branching fraction has been determined in a variety of measurements with an overall precision of approximately 7% yielding a world average [20] (as of April 2008) of $B(B\to X_s\gamma) = (3.52\pm 0.23\pm 0.09)\times 10^4$. Both BABAR and Belle have recently reported results of new inclusive measurements [3][21]. Although theory and experiment are consistent, the fact that the experimental average is on the high end of the theoretical range tends to favours the existence of a heavy charged Higgs with mass around 650 GeV, but this also results in somewhat weaker NP limits than had been quoted previously. It seems unlikely that the experimental world average will be substantially improved by new experimental measurements any time in the immediate future, and in any case the experimental precision already exceeds that of the NNLO SM theory prediction.

5. Conclusion

The asymmetric B-factories currently have extremely large, well understood data samples available for high-statistics studies of flavour physics observables. The presence of a charged Higgs boson potentially modifies rates and other observables in rare decay modes such as $B\to X_s\gamma$ and $B^+\to\ell^+\nu_\ell$. $B\to X_s\gamma$ is experimentally robust and imposes a stringent $\tan\beta$-independent constraint, however this bound is very model dependent. In contrast, $B^+\to\tau^+\nu$ and $B^+\to\mu^+\nu$ searches have only relatively recently been approaching sensitivity to the SM rate. Charged Higgs bounds from leptonic decays constrain quite heavy masses at large $\tan\beta$. These bounds are relatively model-independent, but suffer from large uncertainties in the SM branching fraction prediction.

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