Light Higgses and Dark Matter at Bottom and Charm Factories

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Neither Dark Matter nor scalar particles in the Higgs sector are ruled out at energies accessible to bottom and charm factories. In Dark Matter searches, the error on the mass of Dark Matter is ~ 4 GeV in the best LHC studies. For light Dark Matter this could represent a 100% (or more) error. In Higgs searches, the presence of a light singlet Higgs can make the LHC Higgs search difficult, if not impossible. If Dark Matter or a Higgs scalar is light, it will *require* a low-energy machine to precisely determine the couplings. We review the models, modes of discovery and rate expectations for these new particle searches at bottom and charm factories. We also discuss the options for new runs at bottom and charm factories relevant for these searches.

1. Introduction

The two major new particles expected at colliders are Dark Matter and the Higgs boson. While some models are now ruled out at energies accessible to bottom and charm factories, it is by no means proven that these *cannot* be light. In fact there exist many attractive models containing light Higgses, for instance supersymmetric models which solve the μ problem via an extended Higgs sector.[1, 2, 3] Furthermore the problem of light Dark Matter and light Higgses are related, as light Dark Matter particle χ, in its simplest incarnation, requires a new light particle U with $m_U \simeq 2m_\chi$ to serve as an s-channel annihilation mediator. A promising possibility for U is that it is a pseudo-scalar higgs, which can be naturally light due to new symmetries which can protect its small mass.[1] In order to ensure discovery, we should look everywhere that is practical for solutions to these problems, and b- and c-factories can perform an important set of new-particle searches.

Apart from the Dark Matter question, in the MSSM it was rigorously shown that an extremely light neutralino is experimentally unconstrained if one drops the assumption of gaugino unification, and the requirement that the neutralino relic density be equal to the Dark Matter relic density.[4] For instance, the Dark Matter problem could be solved in another manner, such as with the QCD axion, rendering the neutralino an insignificant contributor to the relic density of the universe.

2. Dark Matter

In Dark Matter searches, the error on the mass of Dark Matter is ~ 4 GeV at the LHC in the best studies using optimistic models with large cross sections.[1] Ultimately this is due to the resolution of the hadronic calorimeter, since to determine the mass scale, a missing energy event at the LHC can either use the missing transverse momentum, which is a hadronic observable[5] or if purely leptonic observables exist, one can use the changes in slopes and shapes as a function of overall mass scale, which are only weakly correlated.[6]

The only truly fundamental limit on the mass of Dark Matter comes from the Cosmic Microwave Background, which tells us the fraction of the universe that was non-relativistic at the time that photons decoupled, a measurement which includes Dark Matter. Dark Matter must have been non-relativistic at a temperature of about 0.3 eV, therefore the smallest possible mass consistent with the Standard Cosmological Model is about 0.3 eV.

This means that bottom and charm factories are capable of exploring 10 orders of magnitude in the Dark Matter mass. The LHC can expand to the range 5 GeV – 1 TeV, but has no precision below approximately 4 GeV.

We feel that the most compelling motivation for Dark Matter searches at bottom and charm factories is the demonstrable wisdom of a model independent approach. Indeed, the reason $M < 45$ GeV was ignored for so long is due to heavy reliance on models. In particular the Minimal Supersymmetric Standard Model cannot support Dark Matter this light because it would require another charged or colored particle to be lighter than other limits. The secondary particle is necessary to get the annihilation cross section large enough. Nearly all models which cannot support light Dark Matter cannot do so because of limits on *particles other than the Dark Matter candidate itself.* Trivial extensions of these models can generically support light Dark Matter by adding a mediator which is mostly singlet under the Standard Model. Several models demonstrate this explicitly.[1, 7]

The most minimal model possible for Dark Matter is to add only the dark matter candidate χ itself.[8]

[1] These studies all use a large value ~ 100 GeV for the Dark Matter mass. As this mass is brought closer to zero, the resolution on it at the LHC worsens.

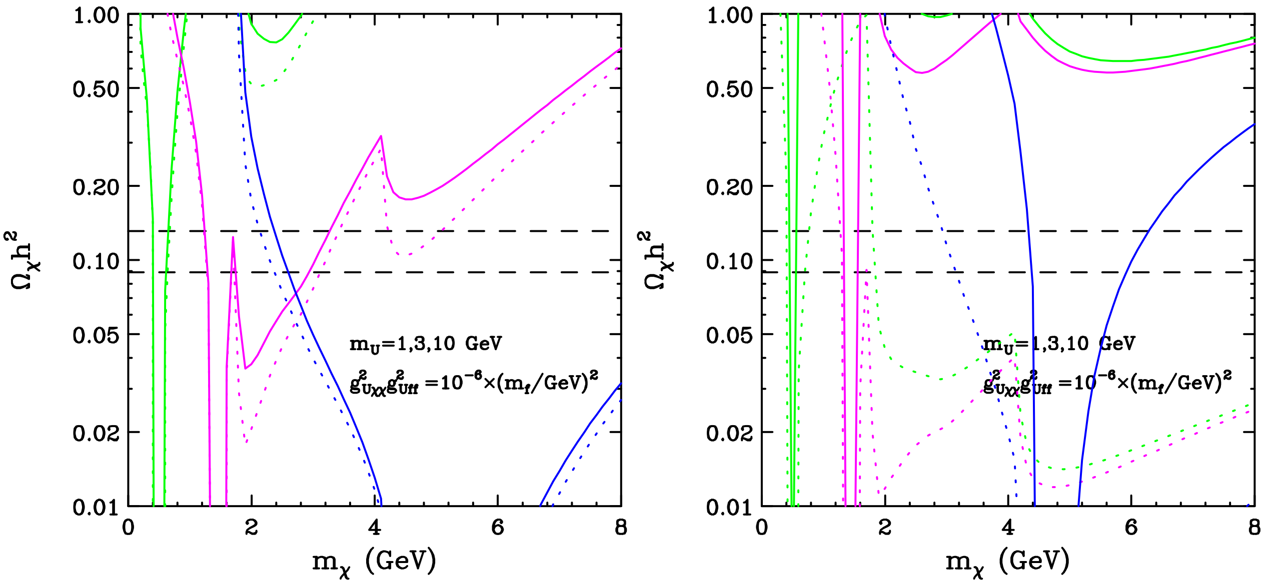

Figure 1: The relic density $\Omega_\chi h^2$ vs the Dark Matter mass M_χ for masses of the mediator $M_U = 1, 3, 10$ GeV. In the left (right) panel, χ is a scalar (fermion). In both panels, U is a scalar (solid) or pseudo-scalar (dotted). These curves move vertically as the free-parameter couplings g_{Uff} and $g_{U\chi\chi}$ are changed. We thank Dan Hooper for his contribution in creating these figures.

However these models generate very heavy Dark Matter candidates, outside the reach of b- and c- factories.

The second most minimal models adds the mediator U as well, which is flavor neutral and couples both to the Standard Model and Dark Matter. these are the models testable at b- and c- factories.

U can be a new gauge boson as proposed in Refs.[7, 9], or a scalar as proposed in [1]. If U is a vector, it is necessarily anomalous, so building a consistent model requires even more matter than the U and χ. We are not aware of any such model in the literature. This is not because it is impossible, but rather because the resulting models are ugly, requiring several symmetry breaking scales and associated Higgses, as well as extra matter to cancel anomalies. If U is a scalar, it can only couple to Standard Model fermions by mixing with the Higgs bosons due to gauge invariance, making its couplings proportional to mass. In the author's opinion, a scalar or pseudo-scalar is a more natural candidate for U. Though as we will see in the next section, a vector U may be easier to discover.

Treating the relic density as a constraint, acceptable models are achieved for (at least) two values of the Dark Matter mass as a function of the mediator's mass, $M_\chi = M_U/2 \pm \epsilon$, as can be seen in Fig.1 This is because the process controlling the annihilation of Dark Matter in the early universe is an s-channel annihilation diagram, rather than t-channel diagrams. In order for a t-channel diagram to dominate the annihilation, the new particle in the t-channel must be charged or colored.[2] This occurs in the MSSM (e.g. "stau co-annihilation") and generates one of the most promising regions of parameter space.

There is experimental evidence that Dark Matter may be light from the INTEGRAL satellite[10], which has detected an anomalously large population of positrons in the galactic center, as suggested in Ref.[9]. If this is from Dark Matter annihilation, it requires $M_\chi \lesssim 3$ MeV.[11]

Another source of evidence is from the DAMA annual modulation signal. As shown in Ref.[12], this is consistent with light Dark Matter due to the lower threshold of Sodium, as compared to heavier elements such as gallium (CDMS) and xenon (XENON).

There are two major modes of discovery for light Dark Matter: invisible meson decay[13, 14] and radiative decay[1, 15]. These are described respectively in the following subsections.

2.1. Invisible Quarkonium Decay

In invisible meson decay, one can make a *naïve* calculation of the branching ratio for a meson.[3] One can

[2]For the masses we consider, $M_\chi < 5$ GeV, annihilation to neutral Higgses or Z-bosons is kinematically disallowed.

[3]Calculation here is expanded and corrected relative to Ref.[13], however the uncertainties and approximations made introduce much larger errors than the difference between the two calculations. This is an order-of-magnitude estimate *only* and little significance can be attached to achieving or exceeding

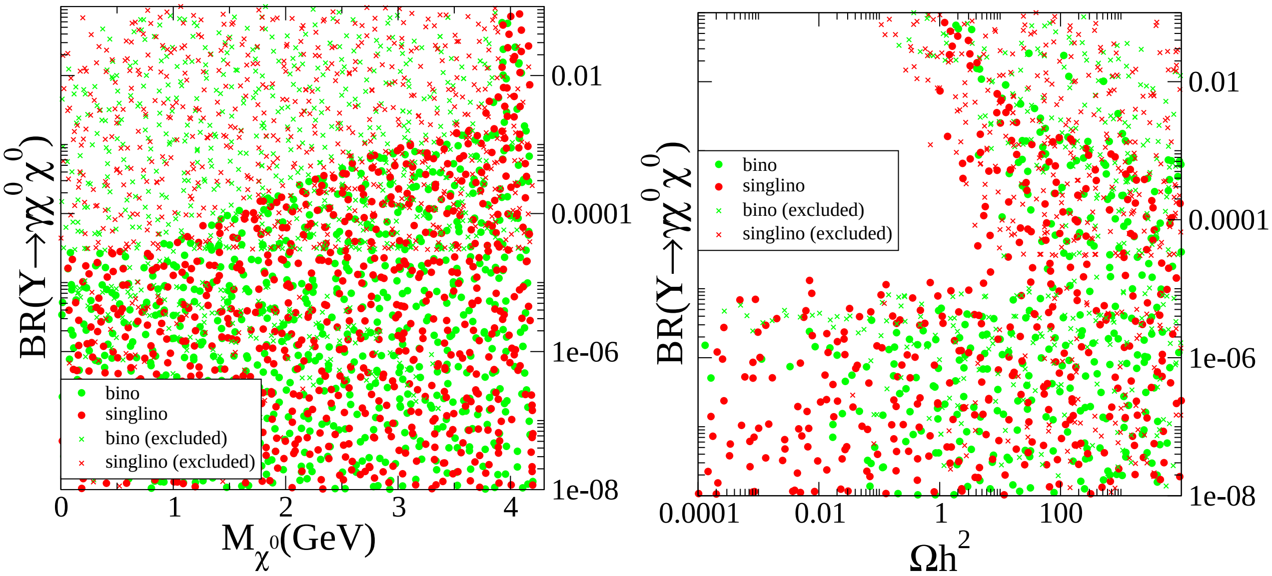

Figure 2: The branching ratio for $\Upsilon(1S) \to \gamma\widetilde{\chi}_1^0\widetilde{\chi}_1^0$ via 3-body decay (i.e. either $m_{A_1} < 2m_{\widetilde{\chi}_1^0}$ or $m_{A_1} > m_\Upsilon$) is plotted vs. the LSP mass (left) and relic density Ωh^2 (right). All points shown are consistent with all LEP constraints. Points marked by an x are excluded by one of: $\Upsilon \to \gamma\widetilde{\chi}_1^0\widetilde{\chi}_1^0$ (3-body decay) (that which is plotted); $\Upsilon \to \gamma A_1$ (2-body decay) with $A_1 \to \widetilde{\chi}_1^0\widetilde{\chi}_1^0$ (2-body decay); or $\Upsilon \to \gamma A_1$ (2-body decay) where the A_1 decays visibly.

get an order of magnitude estimate for the annihilation cross section using

$$\Omega_X h^2 \simeq \frac{0.1\text{pb} \cdot c}{\langle \sigma v \rangle}. \tag{1}$$

Where $\Omega_X = \rho_X/\rho_c$ is the relic density for species X relative to the critical density ρ_c, h is the Hubble constant, and $\langle \sigma v \rangle$ is the thermally averaged annihilation cross section of the DM into Standard Model particles. Using the central value of the WMAP [16] result for $\Omega_X h^2 = 0.113$, we can invert this equation and solve for the required annihilation cross section for light relics

$$\langle \sigma v \rangle = 0.88\,\text{pb} \cdot c. \tag{2}$$

The velocity v appearing here is the Møller velocity, which we approximate by the relative velocity in the center-of-mass frame, $v_{\rm rel} = |v_1 - v_2|$, using $\langle v_{\rm rel}^2 \rangle = 6/x_{FO}$. The approximate temperature at freeze-out is $T = m_\chi/x_{FO}$ where m_χ is the mass of the DM and x_{FO} is an expansion parameter evaluated at the freeze-out temperature that is $x_{FO} \sim 20 - 25$ depending on the model. By approximating that $\langle \sigma v \rangle = \sigma\sqrt{\langle v_{\rm rel}^2 \rangle}$ we can remove the kinematic velocity factor, assuming that the per-particle energy is given by the average energy of the gas $\frac{3}{2}kT$.

We can expand $\langle \sigma v \rangle$ in the velocity at freeze-out to separate s-wave and p-wave components, $\langle \sigma v \rangle = a + bv^2$. Since the Dark Matter annihilates through the U-boson and not the meson we're interested in, the freeze-out may in general occur at a different energy than the invisibly-decaying meson mass. Therefore we also remove the extra v^2 term and solve for b in the p-wave case. These manipulations remove the kinematic factors of the initial state, giving us a cross section that essentially assumes the Dark Matter is massless with respect to our invisibly-decaying meson; that the meson mass is much larger than the center-of-mass energy at freeze-out.

For these assumptions with $x_{FO} = 25$ at freeze-out we have:

$$\begin{aligned} \sigma(\chi\chi \to SM) &= a/v_{\rm rel} \simeq 1.8\,\text{pb}, \qquad (\text{s}-\text{wave}) \\ \sigma(\chi\chi \to SM) &= b/v_{\rm rel} \simeq 7.5\,\text{pb}. \qquad (\text{p}-\text{wave}) \end{aligned} \tag{3}$$

The invisible branching ratio of a hadron can then be estimated by assuming that the time-reversed reaction is the same, $\sigma(f\bar{f} \to \chi\chi) \simeq \sigma(\chi\chi \to f\bar{f})$. Since the meson decays by the meson mixing with the U boson, p-wave suppression factors are not reintroduced for the reverse reaction. We assume that the DM mediator is not flavor changing and that annihilation occurs in the s channel. Therefore, the best-motivated hadrons to have an invisible width are same-flavor quark-antiquark bound states (quarkonia) with narrow widths.

The invisible width of a hadron composed dominantly of $q\bar{q}$ is given approximately by:

$$\Gamma(H \to \chi\chi) = f_H^2 M_H \sigma(q\bar{q} \to \chi\chi) \tag{4}$$

these predictions.

mode	s-wave	p-wave
$\mathrm{BR}(\Upsilon(1S) \to \chi\chi)$	4.2×10^{-4}	1.8×10^{-3}
$\mathrm{BR}(\Upsilon(1S) \to \nu\bar{\nu})$	9.9×10^{-6}	
$\mathrm{BR}(J/\Psi \to \chi\chi)$	2.5×10^{-5}	1.0×10^{-4}
$\mathrm{BR}(J/\Psi \to \nu\bar{\nu})$	2.7×10^{-8}	
$\mathrm{BR}(\eta \to \chi\chi)$	3.4×10^{-5}	1.4×10^{-4}
$\mathrm{BR}(\eta' \to \chi\chi)$	3.7×10^{-7}	1.5×10^{-6}
$\mathrm{BR}(\eta_c \to \chi\chi)$	1.3×10^{-7}	5.3×10^{-7}
$\mathrm{BR}(\chi_{c0}(1P) \to \chi\chi)$	2.7×10^{-8}	1.2×10^{-7}
$\mathrm{BR}(\phi \to \chi\chi)$	1.9×10^{-8}	7.8×10^{-8}
$\mathrm{BR}(\omega \to \chi\chi)$	7.2×10^{-8}	3.0×10^{-8}

Table I Estimated branching ratios for the narrowest mesons. The two columns correspond to the assumption that the Dark Matter annihilation in the early universe occurs in either the s-wave or p-wave. Neutrino branching ratios are from Ref.[17]. All mesons have a branching ratio (even if tiny) to neutrinos.

where f_H is the hadronic form factor (wave function at the origin) for the state H, and M_H is the hadron's mass. Here we ignore final state kinematic and spin factors.

We can predict an approximate expectation for the branching ratios for narrow states. Some of the most promising are shown in Table I: Branching ratios for scalars and pseudo-scalars tend to be smaller since those states are wider.

We emphasize again that this is only an order-of-magnitude calculation. A more precise calculation requires inclusion of kinematic and spin factors, as well as consideration of which fermions the mediator U couples to. Furthermore, the freeze-out of light Dark Matter occurs in the middle of the QCD phase transition, and is much more sensitive to uncertainties due to QCD than heavier Dark Matter. This kind of dark matter is also annihilating through a narrow pole, which must be treated carefully.[18] Narrow poles arise due to the U boson itself, as well as numerous QCD resonances.

Several of these measurements have now been performed including $\Upsilon(1S) \to \chi\chi$[19, 20]; $\eta \to \chi\chi$ and $\eta' \to \chi\chi$[21]; and now $J/\Psi \to \chi\chi$[22].

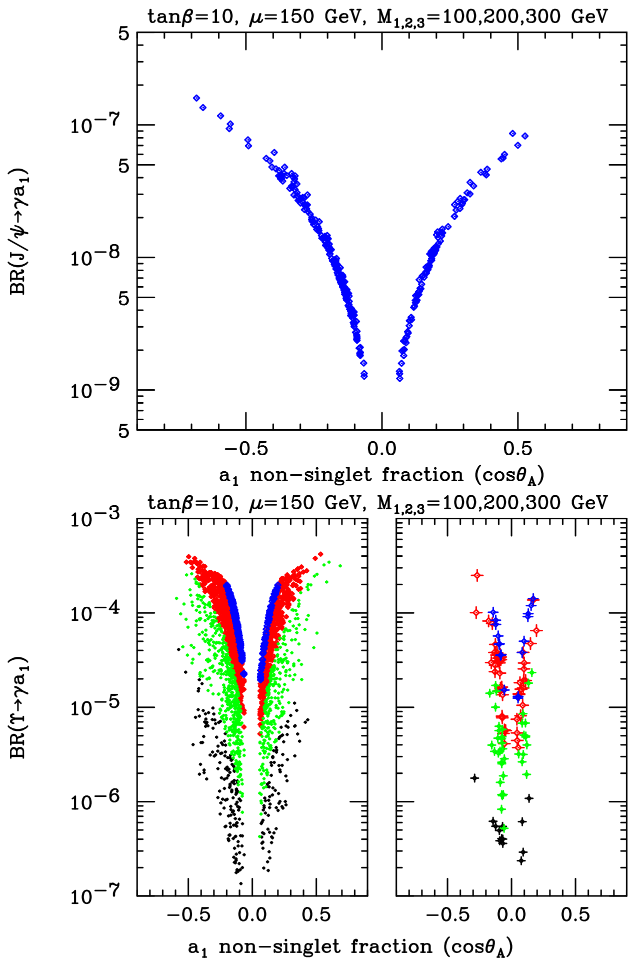

Figure 3: Branching ratio of the J/Ψ (top) and Υ (bottom) into a photon and lightest pseudo-scalar Higgs a_1 in the NMSSM[23]. The a_1 may then decay into Dark Matter (neutralinos) or visible Standard Model particles. The quantity $\cos\theta_A$ parameterizes how singlet-like the a_1 is. $\cos\theta_A = 0$ is decoupled from the Standard Model, while $\cos\theta_A = 1$ indicates that the a_1 is identical to the MSSM A. In the bottom panels, dark (blue) $= m_{a_i} < 2m_\tau$; medium grey (red) $= 2m_\tau < m_{a_i} < 8.4$ GeV; light grey (cyan) $= 8.4\text{GeV} < m_{a_i} < m_\Upsilon$. The plots are for $\tan\beta = 10$ and $M_{1,2,3} = 100, 200, 300$ GeV at scale M_Z. The bottom left plot comes from simply scanning in A_λ, A_κ holding $\mu_{eff} = 150$ GeV fixed. The bottom right plot shows results for the $F < 15$ scenarios among the orange-cross, i.e. $m_{a_i} < 2m_b(pole)$, points of Fig. 1 of Ref.[23].

2.2. Radiative Decay

Radiative decay refers to meson decays into something visible as well as something invisible. This can be flavor changing, such as $b \to s\chi\chi$, in which case this is a next-to-leading-order effect requiring a loop of $W^\pm$ bosons to induce flavor changing.[15] The authors of Ref.[15] found that this radiative decay can be as much as 50 times larger than the similar process radiating neutrinos. [4] Other modes include $\Upsilon \to \gamma\chi\chi$ and $J/\Psi \to \gamma\chi\chi$[1].

In Fig.2.1 we show the branching ratio of J/Ψ and

[4] We prefer to avoid introducing flavor-changing couplings of a Dark Matter mediator, as this is can introduce large corrections to the CKM matrix.

Υ into γa_1 in the NMSSM.[23] The relevance of these plots for Dark Matter are that the a_1 may decay into the neutralino if the bino mass M_1 is decreased to make this mode kinematically allowed (without affecting this branching ratio). This can be done such that it is compatible with all collider constraints including $Z \to invisible$ as described in Ref.[1].

These branching ratios have little to do with the model assumptions of the NMSSM and can be parameterized only with θ_A and β:

$$BR(\Upsilon \to \gamma a_1) \ \propto \ \cos\theta_A \tan\beta \tag{5}$$

$$BR(J/\Psi \to \gamma a_1) \ \propto \ \cos\theta_A \cot\beta, \tag{6}$$

so that experimentally, the only thing one needs worry about is that M_{a_1} is small enough that the mode is kinematically allowed, and any limit can be interpreted in the $\cos\theta_A \tan\beta$ vs. M_{a_1} plane. This covers a vast array of model space including any model with a light Higgs having some singlet admixture. Such Higgses appear in Refs.[1, 2, 3]

3. Higgses

Likewise, the existence of light Higgses can completely destroy the observability of Standard Model Higgs signals at the LHC via decays such as $h_2 \to h_1 h_1$ if it is dominant, where h_2 is a SM-like Higgs and h_1 is a lighter, mostly-singlet Higgs. Even if substantial backgrounds at the LHC can be overcome, the LHC will be unable to get a precise measurement of the lighter h_1 mass. If h_1 decays to $\tau^+\tau^-$ the missing energy makes the mass measurement imprecise. If the h_1 decays to charm, strange, or gluons this renders the dominant Higgs decay entirely hadronic, and likely unobservable at the LHC due to hadronic backgrounds.

By contrast, bottom and charm factories can obtain precise measurements of the mass via the energy of a recoiling photon in the process $\Upsilon \to \gamma h_1$.[23] The h_1 may have branching fractions to both Standard Model matter and Dark Matter.

The mode $\Upsilon \to \gamma H(A)$ was first suggested by Wilczek.[24] This mode is subject to significant radiative and threshold corrections, a comprehensive list of which can be found in Ref.[25]. It was vigorously pursued until about 1995, when it became clear that the LEP accelerator, searching for SM or MSSM Higgses in the Higgsstrahlung modes $e^+e^- \to Zh$ and $e^+e^- \to Ah$ was superior. The best measurements on the Upsilon were made by CLEO,[26] however these remain about a factor of 10 away from being sensitive to a Standard Model Higgs. Existing data can reach the sensitivity required, as CLEO and Belle have approximately 20 times more data collected than that used in these limits. It will be necessary to reach and exceed the Standard Model limits to have sensitivity to Higgses with some singlet admixture.

The LEP measurements told us that no new particles with masses below M_Z have a significant coupling to the Z. However, they tell us little about particles which have small coupling to the Z, and cannot rule out the existence of light particles. Particles with small Z coupling are still allowed and can have interesting couplings to Higgses and fermions.

It is perhaps surprising that a light Higgs could still exist at low energies, and be compatible with all existing direct and indirect limits. However numerous studies have borne this out in a variety of models. All relevant experimental limits have been checked and light Higgses remain consistent with them. Some examples are: In the context of the Two Higgs Doublet Model, $(g-2)_\mu$ (the anomalous magnetic moment of the muon) was examined[27, 28], as well as BR$(b \to s\gamma)$, R_b, A_b, BR$(\Upsilon \to A\gamma)$, BR$(\eta \to A\gamma)$[28]. In the context of the NMSSM, BR$(\Upsilon \to \gamma + X)$[1] was examined and found to be compatible.

We should note also that there is experimental evidence that this decay exists, from considerations of the excess seen at LEP near $M_h = 100$ GeV, fine tuning in the NMSSM,[29], as well as some anomalous events at the HyperCP experiment which seem to indicate a ~ 250 MeV pseudo-scalar decaying to muons[30] that can be verified using radiative decays.

To allow a Higgs to be light, one must reduce its coupling to the Z boson. In the MSSM this is proportional to $\sin(\beta - \alpha)$ for the CP-even state, and zero (at tree level) for the CP-odd state. Thus, by tuning the Higgs mixing angle α to be close to the ratio of the vacuum expectation values $\tan\beta$, this can be achieved. In the MSSM, however, the relationships among masses, α, and β is too constrained to allow only one of the Higgses to be lighter than M_Z while simultaneously satisfying the Higgsstrahlung constraints. Basically, one of the CP-even Higgses has a mass related to the CP-odd Higgs, and the other is related to M_Z. So one cannot bring the h light while simultaneously keeping the A heavy. The A becomes light as well, and generates a large cross section for $e^+e^- \to hA$.

This difficulty comes from the fact that there is not enough freedom in the Higgs mass matrices, and as such is a theoretical constraint caused by one's assumptions, and not experimental proof that there is no light Higgs. In models with more Higgs particles or more freedom in the Higgs self-couplings, the ZZh coupling is more complex, and can be made small. The expansion of the Higgs sector in this manner is well motivated from the need to break any extra gauge symmetries such as a $U(1)'$[2] or $SU(2)_R$, or to solve the MSSM's μ problem.[31] Such particles may also generically be associated with SUSY breaking.

In a more general Two Higgs Doublet Model (2HDM), small coupling to the Z can be achieved with light Higgses because β and α are essentially free parameters. There remains some interesting parameter space in the 2HDM accessible at b- and c- factories, but it is small.[27]

Finally there now exists "Gauge-Phobic Higgs" models in which electroweak symmetry breaking occurs by a combination of an elementary Higgs and breaking by by boundary conditions in an extra dimension.[32] In such models, the Higgses become decoupled from the Z. Their mass again becomes a free parameter and can be light, depending on how much of the symmetry breaking occurs due to the Higgs and how much due to the extra dimension.

4. The Future

As the b-Factories come to the end of their lives, much attention has been given to possible runs off the $\Upsilon(4S)$ resonance. This is an extremely promising idea. A small amount (e.g. weeks to months) of run time at a different energy may provide powerful physics results. Spending that same time on the $\Upsilon(4S)$ will provide only a negligible improvement over the already precise flavor physics results returned by these machines.

The promising options for future runs are on the $\Upsilon(3S)$, $\Upsilon(1S)$, $\Psi(2S)$, and J/Ψ. We have argued for the $\Upsilon(3S)$ due to the existence of the radiative decay $\Upsilon(3S) \to \pi\pi\Upsilon(1S)$,[5] which can be used as a powerful constraint to remove backgrounds for invisible searches[13] and Higgs searches[23]. In addition to the CLEO data collected in the 1990's, Belle has already collected 2.9 fb^{-1}[19] on the $\Upsilon(3S)$.

No new studies have yet been published on the radiative decays $\Upsilon \to \gamma + X$ or $J/\Psi \to \gamma + X$. To improve on the capabilities of the CLEO datasets when searching for rare decays, it is necessary to further reject backgrounds. The single photon signal itself (ignoring the rest of the event) has sizeable backgrounds from direct production of 3-body final states $f\bar{f}\gamma$ which is a background to $\Upsilon \to \gamma a_1 \to \gamma f\bar{f}$. This argument was presented for $\Upsilon \to \gamma\tau^+\tau^-$ in Ref.[23], but holds just as well for other fermions. Due to the high luminosity, BaBar and Belle have higher photon backgrounds in general than CLEO did.

Therefore, for all searches described here, we believe that new runs on the $\Upsilon(3S)$ and $\Psi(2S)$ will be the most significant. A Super-B factory can be even more powerful.[33]

[5] The $\Upsilon(2S)$ has this decay mode also, as used in the invisible Υ search by CLEO[20], however the pions are softer and more difficult to reconstruct.

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