

Proposal for testing lepton universality in upsilon decays at a B factory running at $\Upsilon(3S)$ *

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A proposal is presented for detecting new physics at a B factory running at the $\Upsilon(3S)$ resonance by testing lepton universality to the few percent level in the leptonic decays of the $\Upsilon(1S)$ and $\Upsilon(2S)$ resonances tagged by the dipion in the chain decay: $\Upsilon(3S) \rightarrow \pi^+ \pi^- \Upsilon(1S, 2S)$; $\Upsilon(1S, 2S) \rightarrow \ell^+ \ell^-$, $\ell = e, \mu, \tau$.

1 Introduction and motivation

In the quest for new physics beyond the Standard Model (SM) high luminosity B factories and the LHC will play complementary roles in the near future. In particular, the discovery of the long-awaited Higgs boson(s) is one of the greatest challenges arising with the advent of the so-called LHC era. In certain extensions of the SM, however, one of the non-standard Higgs bosons can be quite (even very) light, making its detection uncertain at the LHC, especially for a Higgs mass below the $b\bar{b}$ threshold. Conversely, a high luminosity B factory would be the ideal place to discover such a light Higgs boson, or put stringent constraints on its existence in different models and scenarios. Moreover, a super B factory [1] can go ahead in this study by performing measurements with an unprecedented accuracy even when running at $\Upsilon(4S)$.

The relevance of (radiative) decays of Υ resonances in the search for a (pseudo)scalar non-standard particle was soon recognized [2, 3, 4]. Let us mention, however, that the Crystal Ball, CLEO, and Argus experimental searches [5, 6, 7] have yielded negative results so far. (No further confirmation was found for a narrow state claimed by Crystal Ball with a mass of around 8.3 GeV.) Basically, in all these searches, a monochromatic photon was expected but no peak was observed in the photon spectrum and narrow states were excluded in the analysis.

In this proposal, we consider the possibility of broader intermediate state, yielding rather non-monochromatic photons in the $\Upsilon \rightarrow \gamma \tau^+ \tau^-$ radiative process. Thus, any photon signal peak would be smeared and probably swallowed up in the background. Nevertheless, new physics might still show up as a (slight) breaking of lepton universality (LU), i.e., the branching fractions (BFs) for the electronic and muonic on the one hand and the tauonic mode on the other hand, would be (slightly) different because of a new physics contribution to the latter.

CLEO recently submitted a paper [8] where the ratio of the tauonic and muonic BFs is examined for all three $\Upsilon(1S, 2S, 3S)$ states. The conclusion was that LU is respected within the current experimental accuracy ($\sim 10\%$), although the measured tauonic BF turns out to be systematically larger than the muonic one at the few percent level.

Table 1: Measured leptonic branching fractions $BF[\Upsilon(nS) \rightarrow \ell\ell]$ (in %) and error bars (summed in quadrature) of $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ resonances (obtained from recent CLEO data and ref.9).

channel:	e^+e^-	$\mu^+\mu^-$	$\tau^+\tau^-$	$R_{\tau/\ell}(nS)$
$\Upsilon(1S)$	2.38 ± 0.11		2.61 ± 0.13	0.10 ± 0.07
$\Upsilon(1S)$		2.48 ± 0.06	2.61 ± 0.13	0.05 ± 0.06
$\Upsilon(2S)$	1.91 ± 0.11		2.11 ± 0.15	0.11 ± 0.11
$\Upsilon(2S)$		1.93 ± 0.17	2.11 ± 0.15	0.09 ± 0.12
$\Upsilon(3S)$	2.18 ± 0.20		2.55 ± 0.24	0.17 ± 0.14
$\Upsilon(3S)$		2.18 ± 0.21	2.55 ± 0.24	0.17 ± 0.15

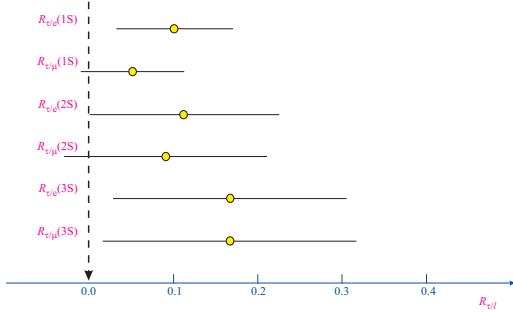


Figure 1: Plot of $R_{\tau/\ell}$ values from Table I. According to a hypothesis test (with LU representing the null hypothesis predicting $\langle R_{\tau/\ell} \rangle = 0$), LU can be rejected to the 1% level of significance. A larger precision is required for any claim; however, a B factory could provide it.

Deviation from LU can be assessed through the ratio defined as [10, 11]

$$R_{\tau/\ell}(nS) = \frac{BF[\Upsilon(nS) \rightarrow \tau\tau] - BF[\Upsilon(nS) \rightarrow \ell\ell]}{BF[\Upsilon(nS) \rightarrow \ell\ell]} = \frac{BF[\Upsilon(nS) \rightarrow \tau\tau]}{BF[\Upsilon(nS) \rightarrow \ell\ell]} - 1; \quad \ell = e, \mu \quad (1)$$

Once these CLEO results are combined with previous BF measurements (see Table I and Fig.1), one can observe an overall 2.6σ effect favoring the tauonic decay mode versus both the electron and muonic ones in all three $\Upsilon(1S, 2S, 3S)$ resonances, implying $R_{\tau/\ell} > 0$.

As advocated in refs.10-12, the LU breaking in upsilon decays would hint at new physics beyond the SM (BSM), pointing out the existence of a light (CP-odd) non-standard Higgs boson. Such a hypothetical particle would mediate the $b\bar{b}$ annihilation into a tauonic pair subsequent to a dipole magnetic (M1) transition (see Fig.2), yielding an unobserved (not necessarily soft) photon according to the process

$$\Upsilon(nS) \rightarrow \gamma \eta_b(n'S)(\rightarrow \tau^+\tau^-); \quad n' \leq n \quad (2)$$

i.e., we consider both allowed (photon energy $\lesssim 100$ MeV) and hindered (photon energy $\lesssim 1$ GeV)

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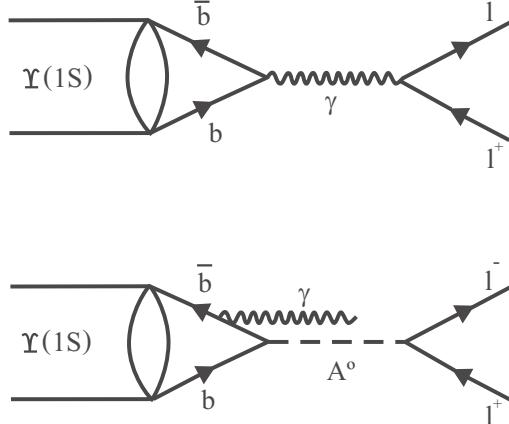


Figure 2: (a): Conventional electromagnetic annihilation of the $\Upsilon(1S)$ resonance into a $\ell^+\ell^-$ pair. (b): Non-standard Higgs-mediated annihilation subsequent to photon emission either on the continuum or through an intermediate $b\bar{b}$ bound state. The Higgs-fermion coupling is proportional to the fermionic mass; hence, only the tauonic decay mode should be sensitive to this NP contribution.

transitions between the Υ and η_b states. Factorizing the decay as a two-step process,

$$BF[\Upsilon(nS) \rightarrow \gamma \tau^+ \tau^-] = BF[\Upsilon(nS) \rightarrow \gamma \eta_b] \times BF[\eta_b \rightarrow \tau^+ \tau^-] \quad (3)$$

where the probability of the M1 transition, $\Upsilon \rightarrow \gamma \eta_b$, can be determined in a potential quark model calculation [13] or using an effective theory of QCD [14].

Leptonic widths and BFs as defined in ref.9 contain corrections of all the orders of QED, including radiated photons. Since the M1 photon in the process (2) would escape undetected because of the experimental technique employed, the NP contribution would be unwittingly ascribed to the tauonic decay mode, thereby enhancing its BF, while the electronic and muonic modes would remain unaltered, ultimately implying the observation of LU breaking in upsilon decays. (Notice that higher order SM processes like the Z^0 exchange, should give negligible contributions.) It is possible, however, to look specifically for the M1 photon although no clean peak can be expected from continuum emission or a broad intermediate state.

In summary, assuming universality breaking as a working hypothesis, the results shown in Table I are compatible with the following interpretation involving new physics:

- There is a light CP-odd (or without definite CP) Higgs particle (denoted as A^0) whose mass is at about 10 GeV. A significant mixing can occur between the A^0 and η_b states if their masses are close enough. Then, the descriptions based on the mixing or on an intermediate η_b state decaying through a CP-odd Higgs boson A^0 as in Eq. (2) should be equivalent to a leading order approximation.
- Even for moderate values of $\tan \beta$ (defined as the ratio of the vacuum expectation values of the Higgs down- and up-doublets [15]), the η_b resonance would decay predominantly into a tauonic pair via a Higgs-mediated annihilation channel (see Fig.2). Hence, a magnetic dipole transition from the Υ would yield an intermediate η_b state subsequently decaying into a $\tau^+ \tau^-$ pair, with $BF[\eta_b \rightarrow \tau^+ \tau^-] \simeq 1$.

- The BFs shown in Table I are compatible with the probability of either allowed or hindered M1 transitions from Υ resonances into η_b , whose estimated BFs [13, 14] are both of the order $10^{-4} - 10^{-3}$. Thus, since $BF[\Upsilon(nS) \rightarrow \ell\ell] \simeq 2\%$, one naturally obtains

$$R_{\tau/\ell}(nS) \approx \frac{BF[\Upsilon(nS) \rightarrow \gamma \eta_b]}{BF[\Upsilon(nS) \rightarrow \ell\ell]} \approx 10^{-2} - 10^{-1} \quad (4)$$

- In addition, considering radiative upsilon decays [2] into an on-shell A^0 particle if kinematically allowed, $\Upsilon \rightarrow \gamma A^0$ occurs, the latter subsequently decays into a tauonic pair $A^0 \rightarrow \tau^+ \tau^-$ with probability near unity for moderate $\tan \beta$ [11]. Setting the reference values ($\tan \beta = 15$, $v = 246$ GeV and $M_\Upsilon - M_{A^0} = 250$ MeV), one obtains

$$R_{\tau/\ell}(nS) \approx \frac{M_\Upsilon^2 \tan^2 \beta}{8\pi\alpha v^2} \left[1 - \frac{M_{A^0}^2}{M_\Upsilon^2} \right] \approx 10^{-1} \quad (5)$$

Let us remark that the $A^0 - \eta_b$ mixing could make the A^0 width larger than expected, yielding quite non-monochromatic photons from radiative Υ decays.

Theoretical arguments supporting the hypothesis of a light CP-odd Higgs boson

From a theoretical viewpoint, the existence of a light pseudoscalar in the Higgs sector is expected in certain extensions of the SM. As an especially appealing example, let us mention the next-to-minimal supersymmetric standard model (NMSSM) where a gauge singlet is added to the MSSM two-doublet Higgs sector, leading to seven Higgs bosons, where five of them neutral of which two are pseudoscalars [15]. The associated phenomenology has to be examined with great attention in different experimental environments [16].

The NMSSM can show an approximate R -symmetry (in the limit that the Higgs sector trilinear soft breaking terms are small) or a U(1) Peccei-Quinn symmetry (in the limit that the cubic singlet term in the superpotential vanishes). In either case, the lightest CP-odd Higgs would be naturally light. This possibility can be extended to scenarios with more than one gauge singlet [17], and even to the MSSM with a CP-violating Higgs sector [18, 19] as LEP bounds can be evaded [20].

Moreover, even Little Higgs models have an extended structure of global symmetries (among which there can appear $U(1)$ factors) broken both spontaneously and explicitly, leading to possible light pseudoscalar particles in the Higgs spectrum. The mass of such pseudoaxions is in fact not predicted by the model, and small values are allowed even of the order of a few GeV [20].

Some experimental results motivating the search for a light Higgs boson in different BSM scenarios

Either the SM or a non-standard Higgs boson has been elusive in all the searches performed so far. However, different experimental measurements might already give some indications about the existence of a light non-standard Higgs. Let us summarize several examples below:

- a) It is important to stress that a light CP-odd Higgs of mass below the $b\bar{b}$ threshold has not been excluded by LEP in different scenarios (see ref.20 and references therein). Interestingly, this possibility is consistent with the event excess detected in the LEP data for a Higgs with SM-like ZZH coupling in the vicinity of 100 GeV, according to the NMSSM as emphasized in refs.21 and 22. Furthermore, the choice of these parameters under the LEP bounds yielding small fine-tuning at small (large) $\tan \beta$ imply nearly always (often) the existence of a relatively light SM-like Higgs boson that decays into two light, perhaps very light, pseudoscalars.

- b) Light dark matter: It is possible that the neutralino is extremely light (100 MeV to 10 GeV) and can annihilate at a sufficiently rate through a light pseudoscalar boson so that the correct dark matter relic density is obtained in the NMSSM [23, 24]. Let us remark that the last and unsuccessful search for light dark matter carried out by Belle and CLEO [25, 26] looking for upsilon invisible decays (following the proposal made in ref.27 only restricts a vector mediator like an extra gauge boson (commonly dubbed U-boson), without affecting the possibility of a (pseudo)scalar mediator like a (CP-odd) Higgs boson.
- c) The $g-2$ muon anomaly would require a light CP-odd Higgs to reconcile the experimental value with the theoretical result when combining one-loop and two-loop contributions [28]. However, large theoretical uncertainties in the leading order hadronic and hadronic light-light contributions as well from experimental results make any conclusion controversial.
- d) Let us note the fact that no η_b state has been found so far despite intensive and dedicated searches. Recently, CLEO carried out a search for $\eta_b(1S)$ and $\eta_b(2S)$ states in hindered magnetic dipole transitions from $\Upsilon(3S)$ with negative results. In fact, one can speculate that this failure is due to a rather broad pseudoscalar 1S_0 bottomonium state as a consequence of the new physics contribution [10]. Notice also that other decay modes [29], used for seeking η_b , can have their BFs lowered with respect to the SM expectations, thereby reducing the chances of η_b to be observed through these decay channels. Besides, the $A^0 - \eta_b$ mixing [30] could alter the properties of both physical states, leading to deviations from the SM expectations. Thus, even the mixed (i.e., physical) A^0 state might be broader than expected due to its η_b component, with important consequences for its detection. We will study this point in detail in a forthcoming paper.

2 The Proposal

The prospects to probe new physics by testing LU have been discussed in several meetings of the quarkonium working group (QWG) and the main conclusions can be read in ref.31. In fact, this proposal is supported by the QWG: see <http://www.qwg.to.infn.it/>, where the action items reproduced below can be found in the BSM section.

Indeed, we think it is extremely interesting that the current B factories could run at the $\Upsilon(3S)$ resonance during a certain period of time in order to collect at least $\sim 10 \text{ fb}^{-1}$ so that LU can be tested with a statistical error below a few percent, as argued below. Systematic uncertainties achieve the utmost importance at this point since CLEO has reported a 5% systematic error in the BF ratio [8]. As we shall see, the cascade decay of $\Upsilon(3S)$ tagged by two charged pions could significantly improve this systematic limit according to our estimates.

In fact, Belle has already performed an engineering run at $\Upsilon(3S)$ collecting an integrated luminosity of 2.9 fb^{-1} , which could be used to test LU. Moreover, the already existing data at $\Upsilon(4S)$ can be used for testing LU by exploiting ISR and dipion transitions as briefly commented below. We therefore propose to carry out the following program:

- i) Measurement of the chain decay where the dipion would tag $\Upsilon(1S, 2S)$, subsequently decaying into electrons or muons:

$$\Upsilon(3S) \rightarrow \pi^+ \pi^- \Upsilon(nS), \Upsilon(nS) \rightarrow \ell^+ \ell^-, \quad n = 1, 2, \quad \ell = e, \mu$$

with the total branching fraction as

$$BF[\Upsilon(3S) \rightarrow \pi^+ \pi^- \Upsilon(1S, 2S)] \times BF[\Upsilon(1S, 2S) \rightarrow \ell^+ \ell^-] \sim (4 - 8) \times 10^{-4}$$

$\Upsilon(1S)$ has an advantage versus $\Upsilon(2S)$ of not requiring the subtraction of cascade decays from the latter into the former. However, $\Upsilon(2S)$ has a larger BF and LU should be tested in its decays as well. On the other hand, muons should possibly be preferable to electrons in the final state.

- ii) Measurement of the chain decay where the dipion would tag $\Upsilon(1S, 2S)$, subsequently decaying into taus, as follows

$$\Upsilon(3S) \rightarrow \pi^+ \pi^- \Upsilon(nS), \Upsilon(nS) \rightarrow \tau^+ \tau^-, \quad n = 1, 2$$

The detection of taus could be done by looking at one-prong decays, mainly focusing on its muonic decay mode. This decay mode should provide important sources of both the statistical and systematic errors for the BFs ratio to be tested.

- iii) The LU in $\Upsilon(3S)$ leptonic decays can also be tested by comparing the rates

$$\Upsilon(3S) \rightarrow \ell^+ \ell^-, \quad \ell = e, \mu, \tau$$

Basically, this analysis should follow similar steps imposing analogous selection criteria for accepted events as in CLEO [8] although the accelerator and detector specifics should obviously make them vary accordingly.

Although we have argued before that one can dispense with the radiative photon in the process (2) (as we are primarily interested in testing LU), let us stress, however, the relevance of detecting it to confirm or reject the existence of a Higgs particle mediating the decay. Therefore, selection cuts on events should be imposed taking into account this possibility, i.e., without a veto that could somehow spoil the detection of photons in the tauonic Υ decays.

On the other hand, the first and relatively easy test of LU can be carried out based on data already collected at $\Upsilon(4S)$ at the B factories. We present several alternatives complementing each another as well as the dedicated run at $\Upsilon(3S)$, as follows

- iv) The dipion decay of the $\Upsilon(4S)$ resonance can tag the decay, i.e.,

$$\Upsilon(4S) \rightarrow \pi^+ \pi^- \Upsilon(nS), \Upsilon(nS) \rightarrow \ell^+ \ell^-, \quad n = 1, 2, \quad \ell = e, \mu, \tau$$

with the total BF of the order

$$BF[\Upsilon(4S) \rightarrow \pi^+ \pi^- \Upsilon(1S, 2S)] \times BF[\Upsilon(1S, 2S) \rightarrow \ell^+ \ell^-] \sim 10^{-6} - 10^{-7}$$

for $\ell = e, \mu$ which probably would require a super B factory [1] for our goal of testing LU, but might deserve further attention by currently running experiments like Belle and BaBar.

- v) A combination of ISR and dipion transitions would allow to reach the Υ resonances as well from the $\Upsilon(4S)$ energy according to the cascade decays:

$$e^+ e^- [\Upsilon(4S)] \rightarrow \gamma_{ISR} \Upsilon(3S, 2S), \quad \Upsilon(3S, 2S) \rightarrow \pi^+ \pi^- \Upsilon(2S, 1S)$$

Hence, the leptonic decays

$$\Upsilon(2S, 1S) \rightarrow \ell^+ \ell^-, \quad \ell = e, \mu, \tau$$

can be used again to compare the tauonic mode versus the electronic and muonic modes. The corresponding cross sections can be estimated to lie in the range 15-60 fb for the two abovementioned cases, leading to several thousands of events for the muonic decay and about one thousand events for the tauonic decay, once the different efficiencies involved in the process are taken into account.

Foreseen statistical error

Let us note that the statistical error is likely to be dominated by the tauonic decay mode. Taking the CLEO analysis [8] as a reference, where about 5×10^6 $\Upsilon(3S)$ decays were collected corresponding to 1.2 fb^{-1} on-resonance, and using the combined BFs of the preceding section (points i) and ii)) for the cascade decays $\Upsilon(3S) \rightarrow \pi^+ \pi^- \Upsilon(1S, 2S)$, $\Upsilon(1S, 2S) \rightarrow \ell^+ \ell^-$ ($\ell = e, \mu, \tau$), one can naively infer that the statistical error of the ratio $R_{\tau/\mu}$ as a function of the integrated luminosity is approximately given by

$$\epsilon_{stat} \simeq \frac{0.07}{\sqrt{L}}; \quad \epsilon_{stat} \simeq \frac{0.07}{\sqrt{N_{days}}}$$

where L stands for the integrated luminosity in units fb^{-1} and N_{days} for the number of data taking days at the $\Upsilon(3S)$ resonance, assuming that one day of data taking corresponds to $\simeq 1 \text{ fb}^{-1}$. For the direct leptonic decays shown in iii), the statistical error almost should follow the same rule. In particular, notice that by setting $L = 2.9 \text{ fb}^{-1}$ (corresponding to the collected luminosity during the engineering run of Belle), one obtains a foreseen statistical error $\simeq 4\%$.

Foreseen systematic error

Estimating the systematic error of $R_{\tau/\mu}$ in this proposal is more difficult than the statistical one as it depends on the experimental method, accelerator, and detector characteristics, chiefly available to the Belle and BaBar Collaborations. Our aim is rather to obtain a reasonable estimate in order to evaluate the feasibility and significance of this proposal as compared to recent CLEO results reporting a systematic error $\epsilon_{syst} \simeq 5\%$ for the ratio $R_{\tau/\mu}$ [8]. We calculate below the foreseen systematic error according to the method based on the cascade decays:

$$\Upsilon(3S) \rightarrow \pi^+ \pi^- \Upsilon(nS), \Upsilon(nS) \rightarrow \ell^+ \ell^-; \quad n = 1, 2, \quad \ell = e, \mu, \tau$$

which should allow one to determine the ratio of leptonic BFs according to the following formula:

$$\frac{BF[\Upsilon(nS) \rightarrow \tau\tau]}{BF[\Upsilon(nS) \rightarrow \ell\ell]} = \frac{N_{\tau\tau} \varepsilon_{\ell\ell}}{N_{\ell\ell} \varepsilon_{\tau\tau}}; \quad n = 1, 2, \quad \ell = e, \mu$$

where $N_{\ell\ell}$ represents the observed number of leptonic decays and $\varepsilon_{\ell\ell}$ represents the reconstruction efficiencies with $\ell = e, \mu, \tau$. Let us remark that the total number of events needed for the evaluation of absolute leptonic BFs (like in ref.32) cancel out in our BFs ratio, thereby avoiding a source of systematic error. Notice also that the decay chains for the tauonic mode and the electronic and muonic modes share a large common part (till the decay and detection of the final leptons) so one might expect an important cancellation of the systematic uncertainty, e.g., for the ratio in the Monte Carlo (MC) simulation of the whole decay chain.

Indeed, the efficiencies $\varepsilon_{\ell\ell}$ can be obtained from a MC simulation where the dipion transition has to be included using a certain model. This is a similar situation to the study of the $\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-$ decay in ref.32, where the Voloshin-Zakharov model [33] was employed, leading to $\simeq 3\%$ as the systematic uncertainty of the reconstruction efficiency. A similar estimate of the systematic error due to the MC simulation was recently reported by Belle for the $\Upsilon(4S) \rightarrow \Upsilon(1S)\pi^+\pi^-$ decay [34] using the Brown-Cahn model [35].

Setting 1% and 2% as reference values for the systematic errors of the trigger and tracking efficiencies, respectively, and keeping conservatively a $\lesssim 3\%$ uncertainty for the ratio of reconstruction efficiencies, the systematic error of $R_{\tau/\mu}$ turns out to be

$$\epsilon_{syst} \lesssim 3.7\%$$

which represents an improvement with respect to the 5% quoted by CLEO. Needless to say, a more accurate evaluation remains to be made by the experimental teams involved directly in the check of LU if this proposal were favorably considered.

3 Summary and final remarks

In this proposal, we present a preliminary study about the possibility of probing new physics by testing LU to the few percent level in upsilon decays in a B factory running at $\Upsilon(3S)$. Furthermore, even with the machine running at $\Upsilon(4S)$, initial state radiation in combination with dipion transitions should permit reaching $\Upsilon(1S, 2S, 3S)$ resonances to carry out the proposed test as well. An integrated luminosity of $\sim 10\text{fb}^{-1}$ at $\Upsilon(3S)$ should suffice to detect/exclude a light Higgs boson of mass about 10 GeV to the 95% CL. The search for light dark matter can also be seen as a related issue to be carried out in a B factory under similar run conditions [27].

From a theoretical viewpoint, there are arguments supporting the existence of a light CP-odd particle in the Higgs spectrum of several scenarios beyond the minimal extension of the SM. The parameter regions allowed in these models are far more extensive than those in the MSSM, with significant consequences for the phenomenology in colliders. From an experimental viewpoint, there are already hints (LEP events excess, g-2 anomaly,...) suggesting the existence of a light pseudoscalar Higgs compatible with the LEP bounds.

The observation of a Higgs boson of mass below the $b\bar{b}$ threshold, chiefly decaying into a tau pair if kinematically allowed, should be quite difficult in LHC experiments but relatively easy at a B factory. We want to stress the role to be played by Belle and BaBar in this regard. According to our estimates, Belle could check LU using their 2.9 fb^{-1} sample already collected in the engineering run at $\Upsilon(3S)$, with a foreseen statistical and systematic precision of the order of the few percent each. Conceivably, BaBar can also perform a similar analysis by using their 400 fb^{-1} integrated luminosity collected at $\Upsilon(4S)$ energy. As a final remark, a super B factory might test LU to an unprecedented precision even when running at $\Upsilon(4S)$ if systematics are well under control.

Lastly, let us stress the relevance of the (even negative) result stemming from this test for constraining model parameters in many scenarios beyond the SM, regarding both the LHC and the prospects of the ILC and a super B factory.

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