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Proposal for testing lepton universality in Upsilon decays at a B-Factory running on the $\Upsilon(3S)$*†

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We present a proposal for detecting new physics at a B-Factory running on 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: $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S,2S)$; $\Upsilon(1S,2S) \to \ell^+\ell^-$, $\ell = e, \mu, \tau$.

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 of an unprecedented accuracy even running on the $\Upsilon(4S)$.

In fact, the relevance of (radiative) decays of Upsilon resonances in the search for a scalar or pseudoscalar non-standard particle was soon recognized [2, 3, 4]. We can mention CLEO and Argus experimental searches [5, 6, 7] having yielded, however, negative results so far. (No further confirmation was found for a narrow state claimed by Argus with a mass 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 a broad intermediate state or continuum emission yielding non-monochromatic photons in the $\Upsilon \to \gamma\ \tau^+\tau^-$ 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 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 between the tauonic and muonic branching fractions (BF's) 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 BF of tauonic decay channel turns out to be systematically larger than the muonic one to the few percent level.

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

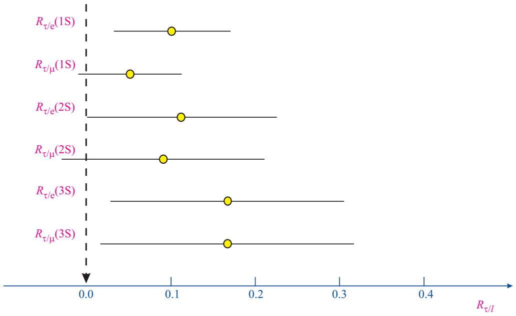

Figure 1: Plot of $R_{\tau/\ell}$ values corresponding to Table 1. According to a hypothesis test (with LU representing the null hypothesis and predicting $< R_{\tau/\ell} >= 0$) lepton universality can be rejected to the 1% level of significance. A larger precision is required for any claim, however;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

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

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

Once those CLEO results are combined with previous BF measurements (see Table 1 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 $R_{\tau/\ell} > 0$.

Indeed, LU breaking in Upsilon decays would open up the possibility of new physics beyond the SM (BSM) [10, 11, 12] eventually 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

$$\Upsilon(nS) \ \to \ \gamma\ \eta_b(n'S)(\to \tau^+\tau^-) \tag{2}$$

where $n' \leq n$, i.e. we consider both allowed (photon energy $\lesssim 100$ MeV) and hindered ($\lesssim 1$ GeV) transitions between Υ and η_b states. Factorizing the decay as a two-step process, we have

$$BF[\Upsilon(nS) \ \to \ \gamma\ \tau^+\tau^-] = BF[\Upsilon(nS) \ \to \ \gamma\ \eta_b] \times BF[\eta_b \to \tau^+\tau^-] \tag{3}$$

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

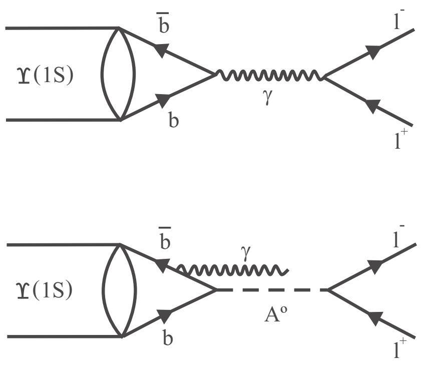

Figure 2: (a): Conventional electromagnetic annihilation of the $\Upsilon(1S)$ resonance into a $\ell^+\ell^-$ pair. (b): Non-standard Higgs-mediated annihilation subsequent to a (soft) photon emission either on the continuum or through an intermediate $b\bar{b}$ bound state. The Higgs-fermion coupling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

Because the M1 photon in the process (2) would escape undetected [1], the NP contribution would be unwittingly ascribed to the tauonic decay mode, enhencing its BF, while the electronic or muonic modes would remain unaltered, ultimately implying LU breaking in Upsilon decays. Notice that higher-order SM processes (like Z^0 exchange) should give negligible contributions.

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 lies at about 10 GeV

- 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), i.e. $BF[\eta_b \to \tau^+\tau^-] \simeq 1$

- Magnetic dipole transitions of Υ resonances would yield intermediate η_b states which, subsequently decaying into $\tau^+\tau^-$ pairs with probability near unity

- The BF's shown in Table 1 are compatible with the probability of either an allowed transition of the $\Upsilon(1S)$ into a $\eta_b(1S)$ state, or a hindered transition from a $\Upsilon(2S)$ or a $\Upsilon(3S)$ into a $\eta_b(1S)$. Indeed, the BF's of allowed and hindered transitions from Upsilon states into a $\eta_b(1S)$ are both of order $10^{-4} - 10^{-3}$ [13, 14]. Thus, since $BF[\Upsilon(nS) \to \ell\ell] \simeq 2\%$, one gets naturally

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

  In addition, one should also consider radiative Upsilon decays into an on-shell A^0 particle, subsequently decaying into a tauonic pair. Setting as reference values: $\tan\beta = 15$, $v = 246$ GeV and $M_\Upsilon - M_{A^0} = 250$ MeV, one obtains

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

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[1] Notice that leptonic widths (and the corresponding BF's) as defined in [9] contain corrections of all orders of QED, including radiated photons; it is possible, however, to look specifically for the M1 photon although no clean peak should be expected from continuum emission or a broad intermediate state

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. Basically, a $U(1)$ symmetry of the super-potential can yield a pseudo-Nambu-Goldstone boson, which for a range of model parameters is significantly lighter than the other scalars. The associated phenomenology has to be examined with great attention in different experimental environments [16].

As a especially appealing example, the NMSSM [15] 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 then evaded [20].

Moreover, also 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 becoming of the order of few GeV [20].

Further 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. We summarize below several examples:

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 [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 [21]. Furthermore, the choice of those 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 a NMSSM or a MNSSM [22, 23]

c) The $g-2$ muon anomaly, which could require a light CP-odd Higgs to reconcile the experimental value with a theoretical two-loop calculation [24]

d) Let us note the fact that no η_b state has been found so far despite intensive searches. Recently CLEO carried out a search for the $\eta_b(1S)$ and $\eta_b(2S)$ states in hindered magnetic dipole transitions from the $\Upsilon(3S)$ with negative results. In fact, one can speculate that this failure is due to a quite broad pseudoscalar ${}^1S_0$ bottomonium state as a consequence of the new physics contribution [10]. Notice also that other decay modes [25], used for seeking the η_b, can have their BF's lowered with respect to the SM expectations, thereby reducing the chances of the η_b to be observed through these decay channels. Besides, CP-odd Higgs-η_b mixing [26] could also alter the properties of both physical states, leading to deviations from the SM expectations

2 The Proposal

The prospects to detect new physics by testing lepton universality have been discussed in several meetings of the Quarkonium Working Group (QWG) and the main conclusions can be read in [27]. 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 extremely interesting that current B factories could run on the $\Upsilon(3S)$ resonance during a certain period of time [2] in order to accumulate $\sim 10\ fb^{-1}$ so that lepton universality could be tested to the few percent level, as argued below. We therefore propose to compare:

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

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

  with total branching fraction:

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

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

- Measurement of the chain decay where the dipion would tag the $\Upsilon(1S,2S)$ decaying into tau's.

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

  Detection of tau's could be done by looking to one-prong decays, mainly focusing on its muonic decay mode.

- Lepton universality in $\Upsilon(3S)$ leptonic decays can be also tested by comparing the rates

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

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 spoil somehow the detection of photons in the tauonic Upsilon decays.

Let us also point out the possibility of using the dipion decay of the $\Upsilon(4S)$ resonance (hence with the machine sitting on this resonance without need of any special run at other energies):

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

with total branching fraction of order:

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

which probably would require a Super B-Factory [1] for our goal, but might deserve further attention by currently running experiments like Belle and BaBar.

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[2] In fact, Belle has already performed an engineering run on the $\Upsilon(3S)$ accumulating several fb^{-1}

Foreseen statistical error

Taking as a reference the CLEO analysis [8], one can infer that the statistical error of the ratio $R_{\tau/\mu}$ as a function of the integrated luminosity is approximately given by:

$$\epsilon_{stat} \simeq \frac{0.08}{\sqrt{N_{days}}}$$

where N_{days} stands for the number of data-taking days on the $\Upsilon(3S)$ resonance. This estimate is approximately the same for either the chain decay or the direct leptonic decay shown above. [3]

Foreseen systematic error

The systematic error is harder to be estimated than the statistical one as it depends on the experimental method, accelerator and detector characteristics. Nevertheless, let us note that the ratio of BF's should be insensitive to some common uncertainties. In addition, no systematic error should be attributed to off-resonance subtraction in the sample of tagged (by the dipion) decays, in contrast to the direct leptonic decays. Hence, taking as a reference value the systematic error obtained by CLEO for $R_{\tau/\mu}$ [8], we make the educated guess:

$$\epsilon_{syst} \lesssim 0.05$$

3 Summary and final remarks

In this proposal we present a preliminary study about the possibility of searching for new physics by testing lepton universality to the few percent level in Upsilon decays in a B-Factory running on the $\Upsilon(3S)$. An integrated luminosity of $\sim 10\ fb^{-1}$ should suffice to detect/exclude a light Higgs boson of mass about 10 GeV to 95%CL. 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 [28].

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 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 at 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 if running on the $\Upsilon(3S)$. Moreover, a Super B-Factory could test LU to an unprecented precision even running on the $\Upsilon(4S)$.

Finally, let us remark 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 a Super B-Factory.

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[3] The statistical error provided by CLEO for the $\Upsilon(3S)$ ratio is 8% corresponding to 1.2 fb^{-1}. This basically corresponds to one day of data-taking at KEKB. On the other hand, the number of expected collected $\Upsilon(1S)$ decays for the tauonic (muonic) mode can be estimated to be about $200/fb^{-1}$ ($2000/fb^{-1}$) yielding altogether a statistical error of order 0.08 in the BF's ratio and similarly in $R_{\tau/\mu}$ for an integrated luminosity of 1 fb^{-1}.

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