

# On The Invisible Decays of the $\Upsilon$ and $J/\Psi$ Resonances

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## Abstract

We estimate the most important corrections to the branching ratios for the invisible decays of quarkonium states, arising from possible extensions of the Standard Model. Among the possibilities considered are the presence of extra  $Z$ -bosons, minimal supersymmetric extensions of the Standard Model with  $R$ -parity violation and decays into Goldstinos. Prospects of detecting these corrections at existing and future  $B$ -factories and  $\tau$ -charm factories are discussed.

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B-meson factories under construction at KEK and at SLAC [1] can deliver  $10^8$   $\Upsilon$ 's and  $\Upsilon'$ 's per year, when they are tuned to run at resonance. Coupled with what is available at CLEO III, these facilities will make it possible for the first time to study in detail invisible decays of these resonances. Such decay modes can be studied by observing the decay  $\Upsilon' \rightarrow \Upsilon + 2\pi$ 's at resonance and tagging on the invariant mass of the dipion system at the  $\Upsilon$ -mass.

Invisible decays of heavy quarkonium states offer a window into what may lie beyond the Standard Model. The reason is that apart from neutrinos, the minimal Standard Model predicts no other channels that these states can decay into. The associated rates for these decays can be computed precisely, and so any observed departure can furnish hints of structures over and above those in the Standard Model. As we will show below, a more complete test of what these structures might be would require similar measurements on the  $J/\Psi$ -invisible decay widths, something which could be achieved at the  $\tau$ -charm factory in the future.

In what follows, we concentrate on what we believe to be the largest among these effects. In particular, we will estimate the branching ratios into neutrinos in the presence of extra  $Z$ -bosons, and R-parity violating effects in supersymmetrized Standard Models, and finally decays into Goldstones.

To begin, we present the Standard Model prediction for the branching ratio of the invisible decays of  $\Upsilon$  and  $J/\Psi$  and their observed decays into electron-positron pairs. To our knowledge the detail formulae have not been given before. Within the Standard Model the invisible mode consists solely of decays into three types of neutrino-antineutrino pairs. Neglecting polarization effects and taking into account  $e^+e^-$  production through a photon only we get

$$\frac{\Gamma(\Upsilon \rightarrow \nu\bar{\nu})}{\Gamma(\Upsilon \rightarrow e^+e^-)} = \frac{27G^2M_\Upsilon^4}{64\pi^2\alpha^2} \left(-1 + \frac{4}{3}\sin^2\theta_W\right)^2 \quad (1)$$

$$= 4.14 \times 10^{-4} ,$$

$$\frac{\Gamma(J/\Psi \rightarrow \nu\bar{\nu})}{\Gamma(J/\Psi \rightarrow e^+e^-)} = \frac{27G^2M_{J/\Psi}^4}{256\pi^2\alpha^2} \left(1 - \frac{8}{3}\sin^2\theta_W\right)^2 , \quad (2)$$

$$= 4.54 \times 10^{-7} ,$$

with  $G$  and  $\alpha$  being the Fermi and the fine structure constants respectively.  $M_{\Upsilon,J/\Psi}$  are masses for the  $\Upsilon$  and  $J/\Psi$  states. These formulas are expected to be correct up to about 2-3%. The major sources of theoretical uncertainty involved in (1) and (2) can be listed as follows:

1. corrections to the  $\Upsilon$  and  $J/\Psi$  wave functions, including QCD corrections and polarization effects,
2.  $e^+e^-$  production through  $Z$ ,
3. electroweak radiative corrections,
4. corrections due to the Higgs boson.

The first correction is not expected to be significant since it similarly modifies the neutrino and electron decay widths, and so the leading order cancels in the branching ratio. The

second correction will introduce a factor  $0.1M_Q^2/M_Z^2$ , and so is not expected to be significant either.

The third correction can be substantial, and thus needs to be considered in a little more detail. In the numerical calculation quoted above, we have included the  $\overline{MS}$ -running of the coupling constants in  $\alpha$ ,  $G$ , as well as in  $\sin^2\theta$ . We have chosen the  $Z$ -mass,  $G$ , and  $\alpha(M_Z)$  as the input parameters and run the other parameters from their values at the  $Z$ -mass down to the low energies where the quarkonia reside. These are by far the most significant contributions. To the accuracy we are working in, of the order of 2-3%, we may ignore threshold effects. Box-type diagrams with double  $Z$  ( $W^+$ ,  $W^-$ ) or photon emission which may be expected to modify the tree level results turn out to be negligible. The largest of these with two internal photon lines vanish due to charge-conjugation symmetry since both  $\Upsilon$  and  $J/\Psi$  are C-odd. The contribution of the remaining box diagram with virtual  $Z$  and  $\gamma$  also makes only a negligible correction to the tree level  $Z$ -mediated  $e^+e^-$ -production and can be discarded as well. Finally, the Higgs correction is vanishingly small simply because we are dealing with virtually massless particles in the final state.

As a result, branching ratios of (1) and (2) are theoretically clean and thus offer a rare opportunity to search for physics beyond the Standard Model if they are relatively large. Among the most viable candidates are supersymmetry (SUSY) and Grand Unified Theories (GUTs). In the case of spontaneously broken SUSY the decays of  $\Upsilon$  and  $J/\Psi$  will produce invisible Goldstinos (or light gravitinos) in addition to the neutrino models. All other particles in the final state are prohibited by kinematical considerations (see [2]). Therefore, measuring the invisible width and comparing it with the SM prediction could provide information about new physics. In the case of SUSY models, we can gain information on the SUSY-breaking scale as well as about the existence of R-parity violating terms in the superpotential.

We first consider the case of decay into light gravitinos denoted by  $\tilde{g}$ . The general structure of the Goldstino interactions is known, and given for example in [3].

$\Upsilon$  and  $J/\Psi$  can decay into Goldstinos via virtual  $Z, \gamma$  in the s-channel and via exchanges of  $b, c$ -squarks in the t-channel. Neglecting the Goldstino exchange effects, the corresponding rates for the  $J/\Psi$  are calculated to be

$$\frac{\Gamma(J/\Psi \xrightarrow{Z} \tilde{g}\tilde{g})}{\Gamma(J/\Psi \rightarrow e^+e^-)} = \frac{9G^2M_{J/\Psi}^8 v^4 \cos^2 2\beta}{4096\pi^2\alpha^2 F^8} \left(1 - \frac{8}{3} \sin^2 \theta_W\right)^2, \quad (3)$$

$$\frac{\Gamma(J/\Psi \xrightarrow{c\text{-squark}} \tilde{g}\tilde{g})}{\Gamma(J/\Psi \rightarrow e^+e^-)} = \frac{9M_{J/\Psi}^2 m_c^{10}}{32\pi^2\alpha^2 m_{\tilde{c}}^4 F^8}, \quad (4)$$

where  $v^2 = v_1^2 + v_2^2 \approx (174 \text{ GeV})^2$ ,  $v_{1,2} = \langle \Phi_{1,2}^0 \rangle$ ,  $\tan \beta = v_2/v_1$ ,  $m_c(\tilde{m}_c)$  is the mass of the  $c$ -quark (squark) and  $F$  is the SUSY-breaking scale. The photon channel is suppressed as compared to the  $Z$  and  $\tilde{c}$  ones since the photon-goldstino coupling contains higher powers of  $F$  and can be neglected in the leading order approximation. Unfortunately, for a reasonable choice for the value of  $F \sim 1 \text{ TeV}$ [3], these rates are extremely small and far beyond the experimental capabilities. Doing the same calculation for the  $\Upsilon$  does not improve matters for gravitino decay modes. The above considerations rule out light gravitinos as candidates for the invisible decays.

Nevertheless, supersymmetry still can affect the invisible width because of R-parity breaking processes. Such processes affect neutrino decay modes through squark exchange. In

terms of superfields, the relevant interactions are generated by a  $\lambda'_{ijk} L_L^i Q_L^j \bar{D}_R^k$  term in the superpotential. Here  $i, j, k$  are the generation indices and we have suppressed SU(2) indices [4]. Expressed in terms of component fields the interaction Lagrangian takes the form

$$\begin{aligned}
-\mathcal{L}_R = & \lambda'_{ijk} [\tilde{\nu}_{iL} \bar{d}_{kR} d_{jL} + \tilde{d}_{jL} \bar{d}_{kR} \nu_{iL} + \tilde{d}_{kR}^* \bar{\nu}_{iL}^c d_{jL} \\
& - (\tilde{e}_{iL} \bar{d}_{kR} u_{jL} + \tilde{u}_{jL} \bar{d}_{kR} e_{iL} + \tilde{d}_{kR}^* (\bar{e}_{iL}^c) u_{jL})] + \text{H.c.}
\end{aligned} \tag{5}$$

where we have neglected mixing among generations. From Eq. (6) it can be seen that the terms leading to neutrino final states involve the down quarks only, and the  $J/\Psi$  width *will not* be affected. It is noteworthy that one needs to take into account non-SM corrections to the neutrino widths only, since their contributions to  $e^+e^-$  production are far less than 0.1% and lead to higher order corrections to the branching ratio. Neglecting possible squark mixings and quark mixings we get

$$\begin{aligned}
\frac{\Gamma(\Upsilon \rightarrow \nu\bar{\nu})}{\Gamma(\Upsilon \rightarrow e^+e^-)} \Big|_{\text{SM+SUSY}} &= \frac{9G^2 M_\Upsilon^4}{64\pi^2 \alpha^2} \left( 2(-1 + \frac{4}{3} \sin^2 \theta_W)^2 + \right. \\
&\left. \left[ -1 + \frac{4}{3} \sin^2 \theta_W + 2 \left( \frac{M_Z^2}{m_{\tilde{b}_R}^2} + \frac{M_Z^2}{m_{\tilde{b}_L}^2} \right) \frac{\cos^2 \theta_W}{g^2} \sum_{i=1}^3 |\lambda'_{i33}|^2 \right] \right)
\end{aligned} \tag{6}$$

One notices that R-breaking contributions add coherently to the SM result and reduce the width. The present experimental constraints on  $\lambda'_{i33}$  are very loose [5] and SUSY corrections may turn out to be quite significant for this reaction. For a SUSY mass of 100 GeV,  $\lambda'_{133} < 0.002$  from  $\nu_e$  mass calculation,  $\lambda'_{233} < 0.4$  and  $\lambda'_{333} < 0.26$  from the ratio of hadronic to leptonic widths at the Z-pole [6]. We note that Eq. (6) also includes an incoherent piece coming from decays into neutrinos of different flavors.

We display in Fig. 1 the branching ratio of Eq. (1) as a function of the parameter  $x(\text{SUSY}) = \sum_{i=1}^3 \frac{|\lambda'_{i33}|^2}{m_{\tilde{b}_i}^2}$  where we have set  $m_{\tilde{b}_i} = m_{\tilde{b}_R} = m_{\tilde{b}_L} = 100\text{GeV}/c^2$  for definiteness.

It is seen that corrections to the SM result as large as 30% are possible for a range of R-parity violating couplings. We have cut off the  $x$  values at the maximally allowed value of  $x_{\text{max}} = 2.2 \times 10^{-5} \text{GeV}^{-2}$  as dictated by experimental bounds only the  $\lambda'$ 's. Similarly the sensitivity of the invisible  $\Upsilon$  decay to the  $Z'$  mass is given in Fig. 1b where now  $X = M_Z^2/M_{Z'}^2$ .

We next consider another unconventional contribution to  $\Gamma(\Upsilon, J/\Psi \rightarrow \nu\bar{\nu})$  - an extra neutral gauge boson,  $Z'$ , which provides an additional annihilation channel.  $Z'$  bosons appear as remnants of a higher symmetry at large energies and have to be sufficiently massive in order to fit current experimental limits. We will concentrate mainly on the superstring-inspired  $E_6$  grand unification model [10,7] and left-right symmetric models [8]. In the models under consideration, the  $Z'$  will correspond to an extra U(1) (for  $E_6$ ) or to a neutral component of  $SU(2)_R$  (for left-right models).

The phenomenology of an extra  $Z'$  is highly model dependent [9]. For the case of  $E_6$  this depends on the breaking of  $E_6$  to the SM group. The details are beyond the scope of this paper. We are only interested in probing  $Z'$  with Eq. (1) and (2). To this end, we first note that we can neglect the  $Z - Z'$  mixing because precision measurements at LEP2 put a bound of  $< 0.0025$  for such mixings [9]. The fermion couplings and hypercharges are uniquely determined by the way the Standard Model is embedded in  $E_6$  [10]. The neutral current process mediated by the  $Z'$  boson involving the fermion  $f$  is given by

$$\mathcal{L}_{NC} = g_E(Y'_{fL}\bar{f}_L\gamma^\mu f_L + Y'_{fR}\bar{f}_R\gamma^\mu f_R)Z'_\mu. \quad (7)$$

where  $g_E = \sqrt{\frac{5}{3}}g \tan \theta_w$ ,  $g$  is the SU(2) gauge coupling, and  $Y'_f$ 's are the hypercharge of the fermions of a given chirality. The relevant charges for the superstring-inspired  $E_6$  are:  $Y'_{cL,bL} = \frac{1}{3}\sqrt{\frac{3}{5}}$ ,  $Y'_{cR} = -\frac{1}{3}\sqrt{\frac{3}{5}}$ ,  $Y'_\nu = -\frac{1}{6}\sqrt{\frac{3}{5}}$  and  $Y'_{bR} = \frac{1}{6}\sqrt{\frac{3}{5}}$ . The result is

$$\frac{\Gamma(\Upsilon \rightarrow \nu\bar{\nu})}{\Gamma(\Upsilon \rightarrow e^+e^-)} \Big|_{\text{SM+SUSY+E}_6} = \frac{9G^2 M_\Upsilon^4}{64\pi^2 \alpha^2} \left( 2\Omega^2 + \left[ \Omega + 2 \left( \frac{M_Z^2}{m_{bR}^2} + \frac{M_Z^2}{m_{bL}^2} \right) \frac{\cos^2 \theta_W}{g^2} \sum_{i=1}^3 |\lambda'_{i33}|^2 \right]^2 \right), \quad (8)$$

where  $\Omega = -1 + \frac{4}{3}\sin^2 \theta_w + \frac{4\cos^2 \theta_w M_Z^2 g_E^2}{M_{Z'}^2 g^2} Y'_\nu (Y'_{bL} + Y'_{bR})$ . Interestingly, the SM result for  $J/\Psi$  width is unaffected by the extra  $E_6$ - $Z'$  boson since  $Y'_{cL} + Y'_{cR} = 0$ . In contrast with R-breaking processes, the  $Z'$  increases the  $\Upsilon$  width. Hence, if both of these new physics sources are present, destructive interference between these non-SM corrections can take place if the parameters are favorable. This would be fortuitous though not impossible.

For the case of the left-right model, both (1) and (2) undergo a certain modification. Assuming  $\frac{M_Z^2}{M_{Z'}^2} \ll 1$ , the mixing angle  $\phi$  between  $Z$  and  $Z'$  can be expressed as [8]

$$\phi \simeq \sqrt{\cos 2\theta_W} \frac{M_Z^2}{M_{Z'}^2}. \quad (9)$$

Then

$$\frac{\Gamma(J/\Psi \rightarrow \nu\bar{\nu})}{\Gamma(J/\Psi \rightarrow e^+e^-)} \Big|_{\text{SM+SUSY+L-R}} = \frac{27G^2 M_{J/\Psi}^4}{256\pi^2 \alpha^2} \left( 1 - \frac{8}{3} \sin^2 \theta_W \right)^2 \Delta^2, \quad (10)$$

where

$$\Delta = 1 - \left( 1 - \frac{2\sin^4 \theta_W}{\cos 2\theta_W} \right) \frac{M_Z^2}{M_{Z'}^2}.$$

One readily obtains the corresponding expression for the  $\Upsilon$  decay width from (8) with

$$\Omega \Rightarrow \left( -1 + \frac{4}{3} \sin^2 \theta_W \right) \Delta. \quad (11)$$

In this case the widths for both quarkonia will decrease as compared to their SM values.

In Fig. 2 we show the sensitivity of the  $\Upsilon$  decay to the extra  $Z$  boson in the left-right symmetric model with  $x(\text{LR}) = M_Z^2/M_{Z'}^2$ . Very similar behaviour for the branching ratio of  $J/\psi$  decay is displayed in Fig. 2b. Evidently, the latter resonance will not be suitable for probing this class of models.

We have argued that because of the theoretically clean nature of the decays a careful measurement of the invisible widths of the heavy quarkonium states can therefore yield constraints on a variety of physics beyond the Standard Model. It is especially useful for studying R-parity breaking terms of the third generation in SUSY models. It is also sensitive

to extra Z bosons of GUTs or the left-right symmetric model. We also showed that the invisible channel will have to be due to the light neutrinos since the other possibility of light gravitinos will not be significant. Neutralinos will also not contribute since a lower bound of 40 GeV has already been established by LEP measurements [11]. If a deviation from the SM value is found in the  $\Upsilon$  decay a similar measurement for the  $J/\psi$  can shed light on the source of new physics.

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## I. FIGURE CAPTIONS

Fig. 1a The branching ratio of  $\Upsilon \rightarrow \nu\bar{\nu}/\Upsilon \rightarrow e^+e^-$  as a function of the parameter  $x(SUSY) = \sum_i |\lambda'_{i33}|^2 / m_{\tilde{b}}^2$  in R-parity violating MSSM.  $\lambda'$  and the  $m_{\tilde{b}}$  are given in the text.

Fig. 1b The branching ratio  $\Upsilon \rightarrow \nu\bar{\nu}/\Upsilon \rightarrow e^+e^-$  as a function of  $x \equiv M_Z^2/M_{Z'}^2$ , for the extra  $Z'$ -boson in E(6) models.

Fig. 2a The branching ratio  $\Upsilon \rightarrow \nu\bar{\nu}/\Upsilon \rightarrow e^+e^-$  as a function of  $x(LR) \equiv M_Z^2/M_{Z'}^2$  in the left-right symmetric model.

Fig. 2b The branching ratio of  $J/\Psi \rightarrow \nu\bar{\nu}/J/\Psi \rightarrow e^+e^-$  as a function of  $x(LR)$ .









