Single π^0 and η transitions from the $\Upsilon(3S)$

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Abstract

CLEO III data are analyzed for evidence of the hadronic decays $\Upsilon(3S) \to \pi^0\Upsilon(1S)$, $\Upsilon(3S) \to \pi^0\Upsilon(2S)$, $\Upsilon(3S) \to \pi^0 h_b$, and $\Upsilon(3S) \to \eta\Upsilon(1S)$. The decays are studied inclusively, as well as exclusively for the transitions to $\Upsilon(1S)$ and $\Upsilon(2S)$ in which the daughter Υ state decays into two leptons. We observe no significant signal in our analysis of these processes, and thus set the following 90% confidence upper limits: $\mathcal{B}[\Upsilon(3S) \to \pi^0\Upsilon(1S)] \leq .013\%$, $\mathcal{B}[\Upsilon(3S) \to \pi^0\Upsilon(2S)] \leq .013\%$, $\mathcal{B}[\Upsilon(3S) \to \pi^0 h_b] \leq .116\%$, and $\mathcal{B}[\Upsilon(3S) \to \eta\Upsilon(1S)] \leq .011\%$.

Introduction

Very few hadronic decays of bottomonia ($\bar{b}b$ have ever been observed. Other than $\pi\pi$ transitions among the vector $\Upsilon(nS)$ bottomonia, there have been no such transitions measured. Only upper limits on the transitions $\Upsilon(3S, 2S) \to \eta\Upsilon(1S)$ and $\Upsilon(2S) \to \pi^0\Upsilon(1S)$ appear in the current edition of the Particle Data Group summary.[1] Furthermore, no branching fraction for the decay of bottomonium to light hadrons has ever been measured. Thus, bottomonium hadronic decays and transitions are on a rather more fragile experimental footing than the corresponding decays of charmonia. Measurement of such transitions in both bottomonium and charmonium systems would be a significant contribution to our understanding of the physics heavy quarkonia.

In the charmonium system, the transitions $\psi(2S) \to \pi^0 J\psi$ and $\psi(2S) \to \eta J\psi$ have both been observed. [1] Such transitions should occur among the vector $\Upsilon(nS)$ states as well, and this in part motivates our study of these channels. In addition, one the key motivations for the study of single π^0 transitions is the possibility of searching for the unseen singlet $h_b(1^1P_1)$ state in the decay $\Upsilon(3S) \to \pi^0 h_b$.[2] A measurement of the displacement of the mass of h_b from the center of gravity of the triplet ^3P_J states, χ_{bJ}, would help determine the nature of the confining part of the $\bar{b}b$ potential, [3] which is thus far unknown. To date, the only heavy quarkonium hyperfine splitting that is known is the $J\psi - \eta_c$ mass difference, [1] so this measurement could significantly impact the understanding the hyperfine interaction in heavy quarkonia.

The large number of $\Upsilon(3S)$ events from CLEO III, approximately 4.7 million, makes feasible the investigation of rare hadronic transitions among the Υ states as have been referred to above. This data sample represents an approximately tenfold increase in statistics compared to CLEO II and allows for more precise measurements of those branching fractions that have been previously measured, as well as for the possible discovery of previously unobserved transitions. The isospin-violating single π^0 transitions between vector states have not previously been observed in the Υ system. The h_b has been searched for previously in the decay $\Upsilon(3S) \to \pi^0 h_b$ for which CLEO set an upper limit for the branching fraction of .27% at 90% confidence [5]. Finally, the decay $\Upsilon(3S) \to \eta\Upsilon(1S)$ has not been observed, and CLEO [4] set an upper limit at 0.22% at 90% confidence. In this paper, we report the investigation of each of these hadronic transitions using the CLEO III $\Upsilon(3S)$ data set.

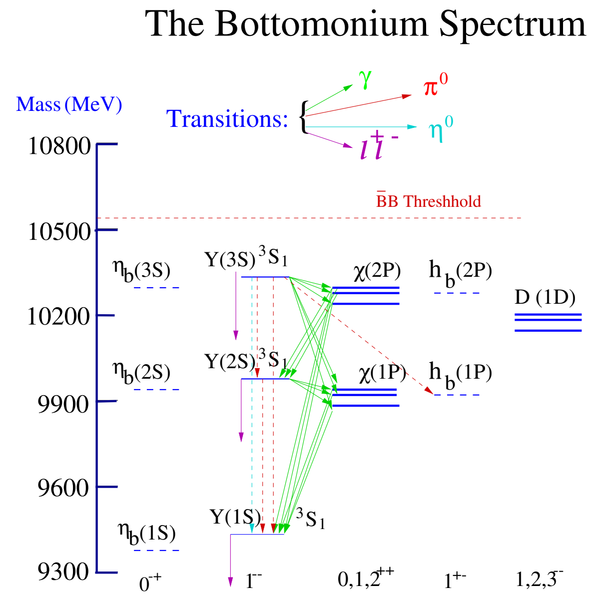

Figure 1. Bottomonium Spectrum

I. Search for $\Upsilon(3S) \to \pi^0\Upsilon(1S)$

We search the recoil mass spectrum against a single π^0 for a peak at the $\Upsilon(1S)$ mass of 9.46 GeV. We subtract weighted sideband regions from the π^0 signal region (within 3.5 sigma of the peak of the reconstructed π^0 mass) to eliminate all background in the recoil mass spectrum except that from real π^0's. This should hopefully eliminate background from the cascade transitions $\Upsilon(3S) \to \chi_b\gamma$, $\chi_b \to \Upsilon(1S,2S)\gamma$ which can fake a π^0 should the photons satisfy the right kinematics causing a false peak in the recoil mass since the background from these cascade transitions in the π^0 mass spectrum is relatively flat according to Monte Carlo. The sideband subtraction method has the additional advantage of a better low-order polynomial fit to the background over a $\sim$200 MeV region. Figure 4 depicts the recoil mass spectrum over the $\Upsilon(1S)$ range. The data are fit to a second order polynomial plus a Gaussian centered at 9.46 GeV with a fixed width of 14 MeV determined from Monte Carlo. This gives us a yield of 1191$\pm$848 events which, assuming a Gaussian likelihood function, corresponds to an upper limit $\mathcal{B}[\Upsilon(3S) \to \pi^0\Upsilon(1S)] \leq .080\%$ at 90% confidence.

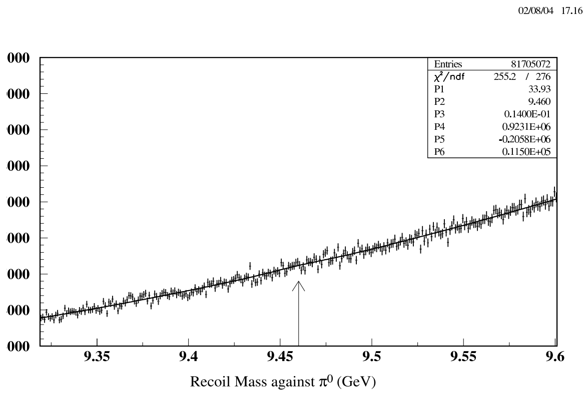

Figure 2. Recoil mass spectrum against a single π^0 with a Gaussian fit at 9.46 GeV over smooth background.

We also study the exclusive mode $\Upsilon(3S) \to \pi^0\Upsilon(1S)$, $\Upsilon(1S) \to \mu^+\mu^-$. We require the reconstructed π^0 mass to fall within 17 MeV (3 sigma) of its mean peak value (134 MeV). We also require at least one muon have an E/p $\leq .4$ to eliminate electrons and other background and that the invariant mass of the μ candidate pair to fall within 230 MeV (4 sigma) of 9.460 GeV. Additionally we require the cosine of the recoil angle between the π^0 momentum and that of the μ candidate pair to be $\geq .9$ to conserve momentum. We require that the difference in energy ($|\Delta E|$) between the sum of the of all the detected particles and the inital energy (twice the beam energy) to be ≤ 207 MeV (3 sigma). Finally we make cuts on the photon energies from the π^0 to eliminate the $\Upsilon(3S) \to \chi_b\gamma$, $\chi_b \to \Upsilon(1S)\gamma$ cascade (Fig. 1). We require the lower-energy photon to be between 133 and 363 MeV and the higher-energy photon to be less than 724 MeV in order to reject photons arising from the two-photon cascade transitions to $\Upsilon(1S)$ via both $\chi_b(1P)$ and $\chi_b(2P)$ intermediate states. These numbers were determined analytically while accounting for a roughly-estimated 10 MeV measurement error and tested on Monte Carlo. The data subject to these cuts are shown in Figure 3. The expected background from photon pairs not arising from π^0's (estimated using sidebands of 3-6 sigma from from the π^0 mass) is shown in Figure 4. The data show no excess above the expected background. Thus with an efficiency of 0.30 for these cuts, which we derived from analysis of a sample of 5000 signal Monte Carlo, we obtain $\mathcal{B}[\Upsilon(3S) \to \pi^0\Upsilon(1S)] \leq .013\%$ at 90% confidence.

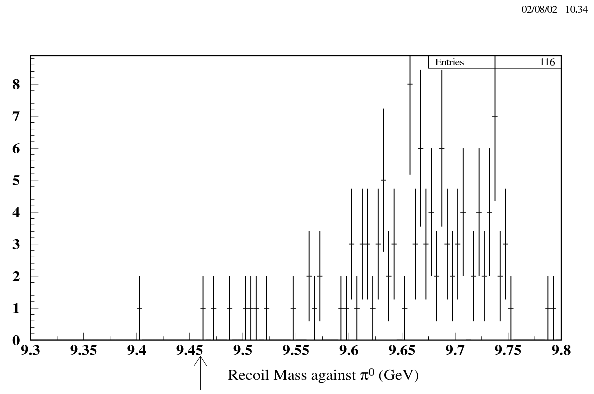

Figure 3. Recoil mass spectrum against a single π^0 after $\Upsilon(3S) \to \pi^0\Upsilon(1S)$, $\Upsilon(1S) \to \mu^+\mu^-$ exclusive mode cuts are applied.

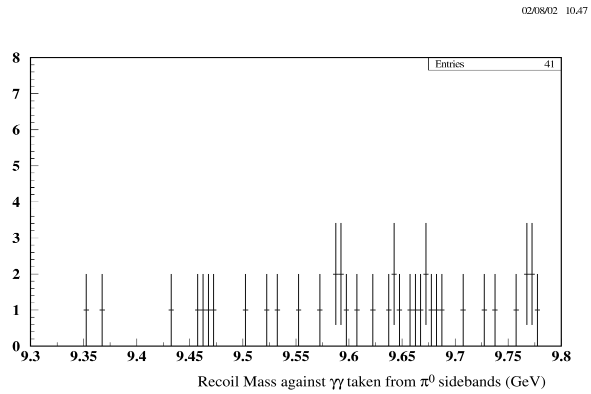

Figure 4. Recoil mass spectrum against photon pairs taken from the π^0 sideband regions described in the text after $\Upsilon(3S) \to \pi^0\Upsilon(1S)$, $\Upsilon(1S) \to \mu^+\mu^-$ exclusive mode cuts are applied.

II. Search for $\Upsilon(3S) \to \pi^0\Upsilon(2S)$

We search inclusively for the process $\Upsilon(3S) \to \pi^0\Upsilon(2S)$ using the same technique as described in Section I. Figure 5 depicts the recoil mass spectrum over the $\Upsilon(2S)$ range. The data are fit to a second order polynomial plus a Gaussian centered at 10.023 GeV with a fixed width of 8 MeV (determined from Monte Carlo). We obtain a yield of -323$\pm$2194 events which, assuming a Gaussian likelihood function, corresponds to an upper limit $\mathcal{B}[\Upsilon(3S) \to \pi^0\Upsilon(2S)] \leq .143\%$ at 90% confidence.

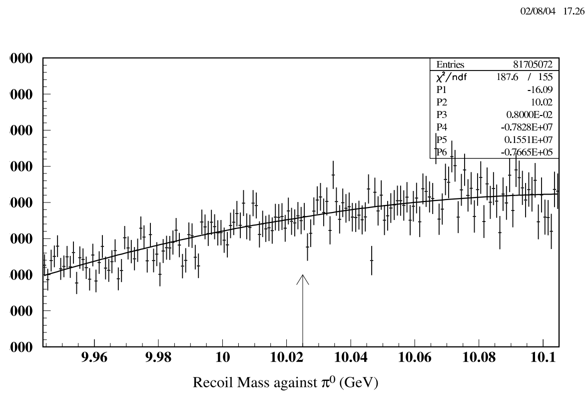

Figure 5. Recoil mass spectrum against a single π^0 with a Gaussian fit at 10.023 GeV over smooth background.

We also search for the exclusive decay $\Upsilon(3S) \to \pi^0\Upsilon(2S)$, $\Upsilon(2S) \to \mu^+\mu^-$. We place the same cuts as in the exclusive $\pi^0\Upsilon(1S)$ channel except for the photon energy cuts which no longer need to account for $\chi_b(1P)$ transitions. To obtain maximal efficiency, we only need to place a cut on the higher-energy photon from the π^0 requiring it to be less than 192 MeV to account for $\chi_b(2P) \to \Upsilon(2S)\gamma$ and no cut on the lower-energy photon. The data with these cuts applied are shown in Figure 6. Figure 7 shows the same cuts applied to a 3-6 sigma sideband region showing the expected background from non-π^0 events. The data show no excess above the expected background; thus with an efficiency for these cuts of .16, we obtain $\mathcal{B}[\Upsilon(3S) \to \pi^0 \Upsilon(2S)] \leq .013\%$ at 90% confidence.

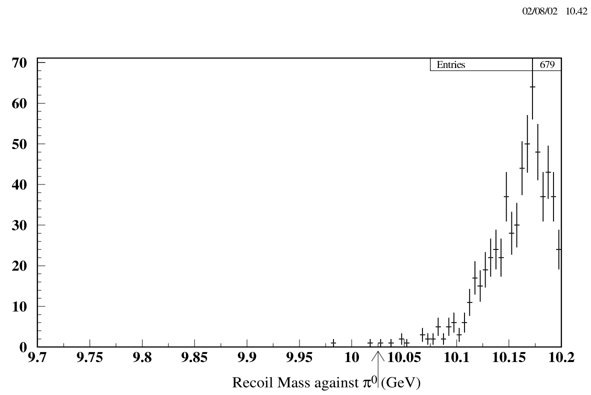

Figure 6. Recoil mass spectrum against a single π^0 after $\Upsilon(3S) \to \pi^0\Upsilon(2S)$, $\Upsilon(2S) \to \mu^+\mu^-$ exclusive mode cuts are applied.

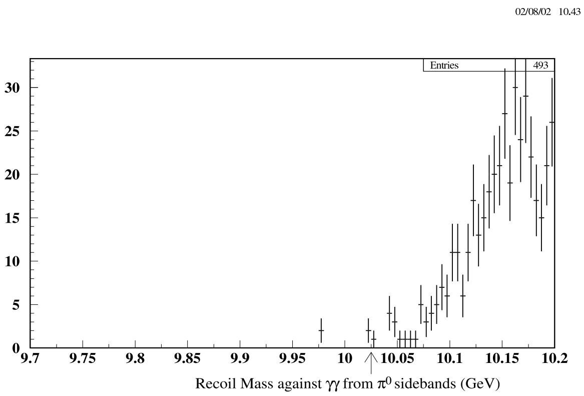

Figure 7. Recoil mass spectrum against photon pairs taken from the π^0 sideband regions described in the text after $\Upsilon(3S) \to \pi^0\Upsilon(2S)$, $\Upsilon(2S) \to \mu^+\mu^-$ exclusive mode cuts are applied.

III. Search for $\Upsilon(3S) \to \pi^0 h_b$

We can search for the decay process $\Upsilon(3S) \to \pi^0 h_b$ inclusively by searching the recoil mass spectrum against a single π^0 near the expected h_b mass of 9.9 GeV, the center of gravity mass of the triplet $\chi_b(1P)$ states. Using the same sideband subtraction presented in section I, we fit the data along a 200 MeV range centered at 9.9 GeV to a second order polynomial plus a Gaussian signal with a fixed width of 10 MeV determined from Monte Carlo. Figure 7 shows the fit for an h_b mass of 9.900 GeV. Figure 8 shows the amplitude and error of the best fit Gaussian as we vary the h_b mass from 9.8 to 10.0 GeV in 1 MeV steps. Within 10 MeV of 9.9 GeV, we find the greatest yield to be -808±1732 events from which we obtain $\mathcal{B}[\Upsilon(3S) \to \pi^0\Upsilon(1S)] \leq .116\%$ at 90% confidence.

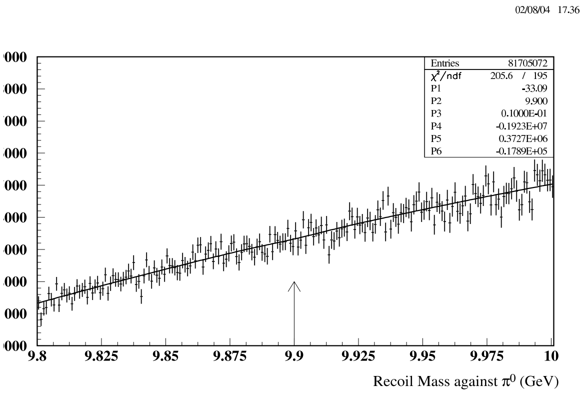

Figure 8. Recoil mass spectrum against a single π^0 with a Gaussian fit at 9.9 GeV over smooth background.

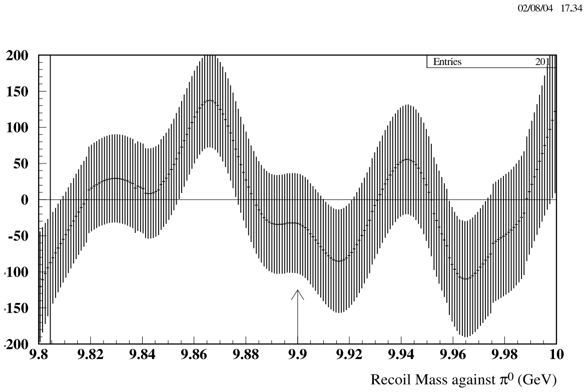

Figure 9. Amplitude of best fit Gaussian plotted as a function of the fixed mean assumed in the fit. These results were obtained by fitting the data shown in Figure 8.

IV. Search for $\Upsilon(3S) \to \eta\Upsilon(1S)$

We study the η decay in both the $\gamma\gamma$ and $\pi^+\pi^-\pi^0$ modes. For the inclusive study of $\Upsilon(3S) \to \eta\Upsilon(1S)$, $\eta \to \gamma\gamma$ we require the reconstructed η mass to fall within 38 MeV (3 sigma) of the η peak at 546 MeV. We also place the same photon energy cuts as in Section I to account for the photon cascades via the χ_b states. Figure 9 shows the best fit to a second order polynomial background and Gaussian signal of width 11 MeV while Figure 10 shows the change in Gaussian amplitude as we vary the mean along the 220 MeV region. The background curve provides a good fit well oustide the region shown. The large region of high yield in Figure 40 from about 9.45 to 9.51 indicates a large uncertainty in our calculated yield at any particular recoil mass. While the amplitude of the fitted Gaussian at 9.46 GeV is many sigma away from zero, more studies will be needed before we can determine if there is evidence for a $\Upsilon(3S) \to \eta\Upsilon(1S)$ signal in this mode.

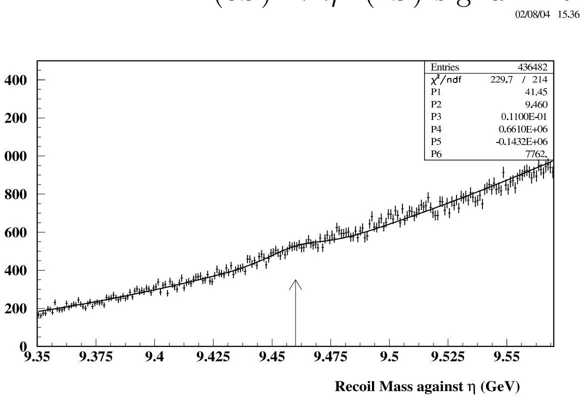

Figure 10. Recoil mass spectrum against a single η in the $\eta \to \gamma\gamma$ mode with a Gaussian fit at 9.46 GeV over smooth background. ($\eta \to \gamma\gamma$)

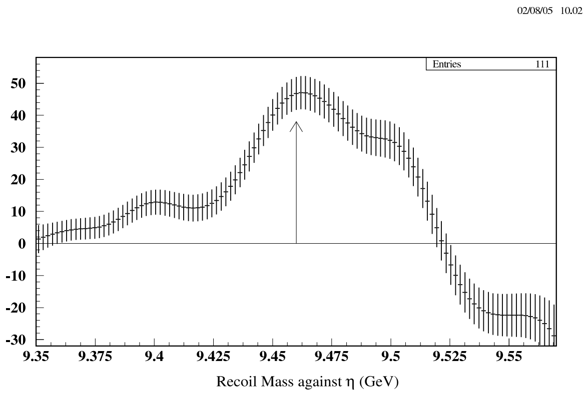

Figure 11. Amplitude of best fit Gaussian plotted as a function of the fixed mean assumed in the fit. These results were obtained by fitting the data shown in Figure 10.

In the exclusive channel $\Upsilon(3S) \to \eta\Upsilon(1S)$, $\Upsilon(1S) \to \mu^+\mu^-$, we place the same 38 MeV cut on the reconstructed η mass about 546 MeV, although there is no evidence of a η peak in the reconstructed η mass as there was in the inclusive mode. As in other analysis, we require one lepton track to have E/p $\leq$ .4, thus consistent with a muon track. We place a 4 sigma (222 MeV) cut from 9.46 GeV on the μ pair invariant mass, as well as require the cosine of the recoil angle between the η momentum and that of the μ pair to be $\geq$ .9 and that $|\Delta E|$ be less than 330 MeV (3 sigma). Finally, we place the same photon energy cuts as in the inclusive mode to eliminate the photon cascades via the χ_b states. Figure 14 shows the data after these cuts, and Figure 15 shows the cuts applied to a 2-4 sigma sideband about the η mass. We see no signal excess over the expected background. Our efficiency with these cuts is .34 from which we obtain $\mathcal{B}[\Upsilon(3S) \to \eta\Upsilon(1S)] \leq .016\%$ at 90% confidence.

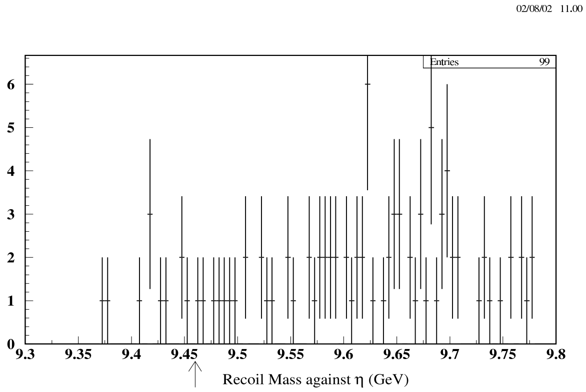

Figure 12. Recoil mass spectrum against η after $\Upsilon(3S) \to \eta\Upsilon(1S)$, $\Upsilon(1S) \to \mu^+\mu^-$ exclusive mode cuts are applied. $(\eta \to \gamma\gamma)$

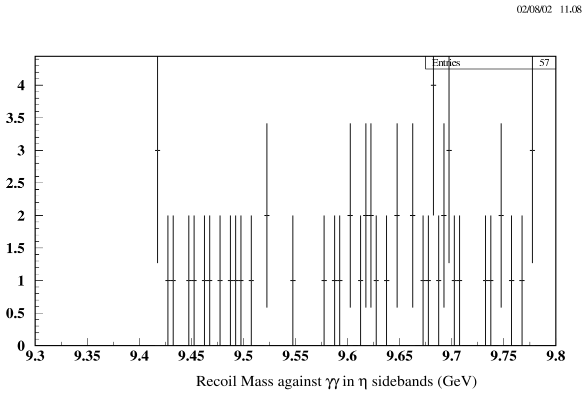

Figure 13. Recoil mass spectrum against photon pairs taken from the η sideband region described in the text after $\Upsilon(3S) \to \pi^0\Upsilon(1S)$, $\Upsilon(1S) \to \mu^+\mu^-$ exclusive mode cuts are applied. $(\eta \to \gamma\gamma)$

For the inclusive study of $\Upsilon(3S) \to \eta\Upsilon(1S)$, $\eta \to \pi^+\pi^-\pi^0$ we first require dE/dx of the charged pion candidates to be within 3 sigma of the expected value for a pion and that the reconstructed π^0 mass be within 20 MeV (3.5 sigma) of the peak (134 MeV). We then create a sideband subtracted plot of recoil mass against the η using 5-10 sigma sidebands and a $\leq$ 3 sigma signal region. The recoil mass near 9.46 GeV is shown in Figure 16 and fit to a second order polynomial background plus a Gaussian curve centered at 9.46 GeV with 8 MeV width determined by Monte Carlo. Figure 44 shows a scan over the region plotting Gaussian amplitude and error over a fixed smooth background versus recoil mass. At 9.46 GeV we find a yield of 1085$\pm$502 which, assuming Gaussian likelihood, corresponds to an upper limit $\mathcal{B}[\Upsilon(3S) \to \eta\Upsilon(1S)] \leq .652\%$ at 90% confidence.

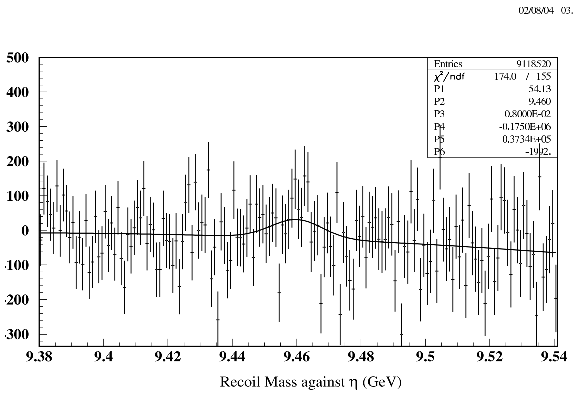

Figure 14. Recoil mass spectrum against a single η in the $\eta \to \pi^+\pi^-\pi^0$ mode with a Gaussian fit at 9.46 GeV over smooth background. ($\eta \to \pi^+\pi^-\pi^0$)

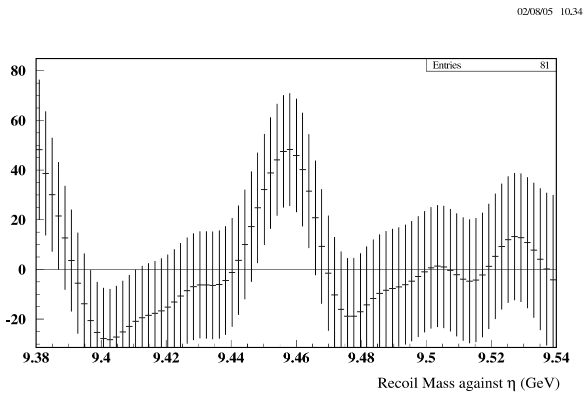

Figure 15. Amplitude of best fit Gaussian plotted as a function of the fixed mean assumed in the fit. These results were obtained by fitting the data shown in Figure 14.

In the corresponding exclusive channel $\Upsilon(3S) \to \eta\Upsilon(1S)$, $\Upsilon(1S) \to \mu^+\mu^-$, we place the same cuts on the charged pion candidates and the π^0 candidate as in the inclusive mode. We also place the same muon, μ pair invariant mass, and recoil angle cut as in the $\eta \to \gamma\gamma$ exclusive mode, and require $|\Delta E| \leq 100$ MeV. We place a cut on the reconstructed η mass of 547$\pm$40 MeV though there is no evidence of an η peak in the mass spectrum. The data with cuts applied is shown in Figure 16, and a 40-80 MeV (10-20 sigma determined by the η mass width in the inclusive mode) sideband region is shown in Figure 17. We find no signal excess above the expected background. Our efficiency with these cuts is .27 from which we obtain a $\mathcal{B}[\Upsilon(3S) \to \eta\Upsilon(1S)] \leq .033\%$ at 90% confidence.

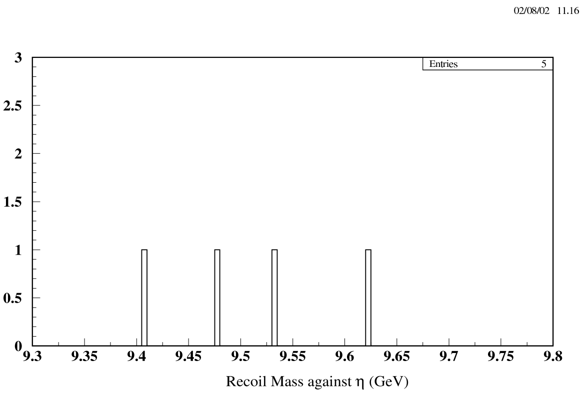

Figure 16. Recoil mass spectrum against η after $\Upsilon(3S) \to \eta\Upsilon(1S)$, $\Upsilon(1S) \to \mu^+\mu^-$ exclusive mode cuts are applied. ($\eta \to \pi^+\pi^-\pi^0$)

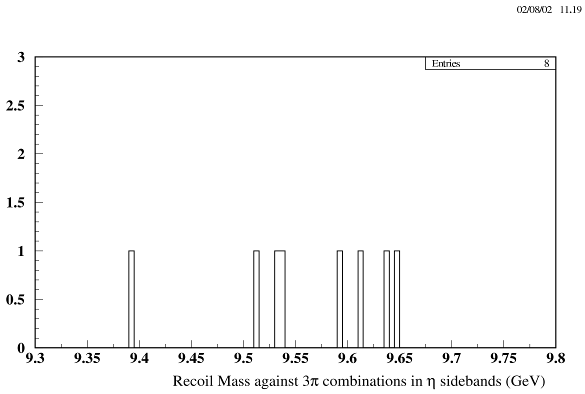

Figure 17. Recoil mass spectrum against $\pi^+\pi^-\pi^0$ combinations taken from the η sideband regions described in the text after $\Upsilon(3S) \to \pi^0\Upsilon(1S)$, $\Upsilon(1S) \to \mu^+\mu^-$ exclusive mode cuts are applied. ($\eta \to \pi^+\pi^-\pi^0$)

We can further combine the statistics for the exclusive η decay modes giving a $\mathcal{B}[\Upsilon(3S) \to$

$\eta\Upsilon(1S)] \leq .011\%$ at 90% confidence.

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Footnotes and References

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2. M. B. Voloshin, Sov. J. Nucl. Phys. 43, 1011 (1986).
3. See, for example, J. Pantaleone and S.-H. H. Tye, Phys. Rev. D37, 3337 (1988), and V. Gupta and R. Kögerler, Phys. Rev. D37, 740 (1988).
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