ARTICLES

Study of $\pi^+\pi^-$ transitions from the $\Upsilon(3S)$ and a search for the h_b

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We have investigated the transitions $\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(1S)$, $\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(2S)$ and the cascade process $\Upsilon(3S)\rightarrow\Upsilon(2S)+X,\Upsilon(2S)\rightarrow\pi^+\pi^-\Upsilon(1S)$, both in the exclusive decay mode, with the daughter Υ state decaying into two leptons, and in the inclusive decay mode, with the daughter Υ state decaying hadronically. Results are presented on the branching fractions and properties of the $\pi^+\pi^-$ system. The $\pi^+\pi^-$ invariant-mass spectra for the decays $\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(1S)$ and $\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(2S)$ are measured and compared with theoretical predictions. We also present the results of a search for the $h_b(1\,^1P_1)$ and $\Upsilon(1\,^3D)$ states in inclusive $\Upsilon(3S)$ decays, and for the exclusive decay $\Upsilon(3S)\rightarrow\eta\Upsilon(1S)$.

I. INTRODUCTION

The bound-state Υ resonances (see Fig. 1) provide an excellent laboratory for studying the interactions of heavy quarks. Along with the masses and widths of these resonances, the photon and $\pi\pi$ transitions between the states provide further information on the heavy-quark interactions. Branching fractions for the decays $\psi' \to \pi^+\pi^-(J/\psi)$ (Refs. 1 and 2), $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1s)$ (Refs. 3–5), $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ (Refs. 6–10), and $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(2S)$ (Ref. 5) have been measured and agree with theoretical expectations. In this paper, we present new, more precise measurements of the branching fractions for the $\pi^+\pi^-$ transitions of the $\Upsilon(3S)$. From the measured number of $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ decays we infer the total $\Upsilon(3S) \to \Upsilon(2S)$ branching fraction. We also give the first upper limit on the branching fraction for the exclusive decay $\Upsilon(3S) \to \eta\Upsilon(1S)$.

The $\pi^+\pi^-$ transitions also allow the study of other $b\bar{b}$ resonances which cannot be produced directly in e^+e^- interactions. Examples are the $h_b(1\,^1P_1)$ and $\Upsilon(1\,^3D)$ states (see Fig. 1), which could be produced in the decay of the $\Upsilon(3S)$. We present the results of a search for the h_b and $\Upsilon(1\,^3D)$ states.

Quantum chromodynamics describes the hadronic transitions between heavy-quarkonium states as the emission of gluons by the heavy quarks followed by the conversion of the gluons into light hadrons. Within the framework of heavy-quark potential models, the $\pi\pi$ decay rates can be calculated from a multipole expansion of the gluon fields.[11–14] The properties of the $\pi\pi$ system are constrained by applying partial conservation of the axial-vector current.[12,15] Previous studies[3–5] of the $\pi^+\pi^-$ invariant-mass spectrum in the transition $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$ suggested that the spectrum was approximately uniform, in contrast with the transitions $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ and $\psi' \to \pi^+\pi^-(J/\psi)$, which are strongly peaked toward high values of $\pi^+\pi^-$ invariant mass. Our previous publication[3] showed that the $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$ spectrum could not be fit with any of the then published models. We present a new detailed study of the $\pi^+\pi^-$ invariant-mass spectrum for the $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$ decay, comparing it with predictions from many theoretical models. We also discuss recent theoretical work on the subject. An improved detector has allowed us to measure the $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(2S)$ dipion invariant-mass spectrum with high statistics. We also fit this distribution to various theoretical predictions.

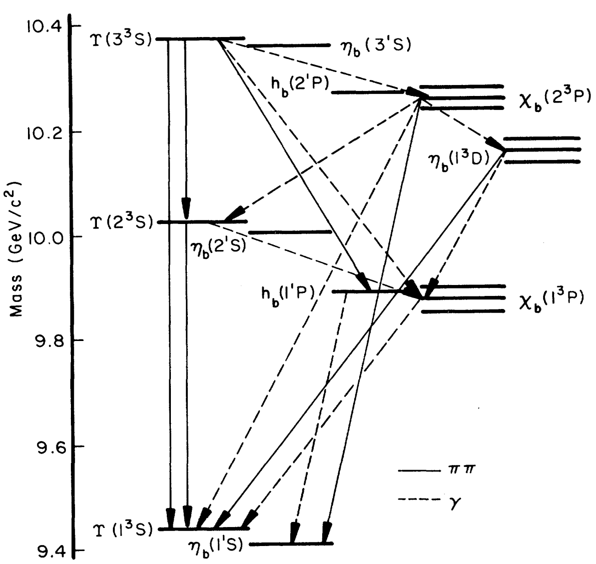

FIG. 1. The spectroscopy of the lowest-mass Υ resonances showing some of the allowed dipion (solid lines) and photon (dashed lines) transitions.

II. ANALYSIS

We present these new results from the decay of the $\Upsilon(3S)$ resonance using the CLEO detector operating at the Cornell Electron Storage Ring (CESR). Our previously published results[3] on $\Upsilon(3S)$ decay contained 33 pb^{-1} of data corresponding to $158\,000 \pm 4100$ $\Upsilon(3S)$ decays[16] (designated as data sample 1). We report here on a new data sample (designated as data sample 2) using an improved detector and containing 51 pb^{-1} of data corresponding to $237\,000 \pm 6800$ $\Upsilon(3S)$ decays. A reanalysis of data sample 1 is also reported using identical procedures to that used for data sample 2, so that the results from the two samples can be combined with a minimum of systematic uncertainty (see Ref. 17).

The CLEO detector and our hadronic-event selection criteria have been described in detail previously.[18] Here, we briefly discuss the modifications to the CLEO central tracking system which were made between the accumulation of data samples 1 and 2. Charged-particle tracking is done inside a superconducting solenoid of radius 1.0 m which produces a 1.0-T magnetic field. Three coaxial cylindrical drift chambers measure momenta and specific ionization for charged particles. The innermost part of the tracking system is a three-layer straw-tube vertex detector, which gives a position accuracy of 70 μm in the r-ϕ plane. The middle ten-layer vertex chamber[19] measures position with an accuracy of 90 μm in the r-ϕ plane and dE/dx to 14%. The main drift chamber[20] contains 51 layers, eleven of which are strung in stereo angles of 1.9° to 3.5° to the z axis. The chamber provides a position accuracy of 110 μm per hit in r-ϕ and has a dE/dx resolution of 6.5%. Measurements of the track coordinates along the beam direction (z) are achieved by using the stereo layers and cathode strip readouts in the middle vertex detector and the main drift chamber. This system achieves a charged-particle momentum resolution given by $(\delta p/p)^2 = (0.23\%p)^2 + (0.7\%)^2$, where p is in GeV/c. Since the π's from $\Upsilon(3S)$ decay have momenta less than 1 GeV/c, the momentum resolution for these particles is dominated by the multiple scattering in the material inside and between the chambers, and is therefore comparable in the two data samples. For this analysis we used only the central tracking chambers and the outer time-of-flight system. The new tracking system used in data sample 2 substantially increased our efficiency for detecting low-momentum charged particles, particularly in multitrack final states.

We have investigated the transitions (a) $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$, (b) $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S)$, and (c) the cascade process $\Upsilon(3S)\to\Upsilon(2S)+X$, $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$, both in the exclusive mode, with the daughter Υ resonance decaying either to e^+e^- or $\mu^+\mu^-$, and in the inclusive decay mode, with the daughter Υ decaying hadronically. The exclusive decay chain for transition (c) included $\Upsilon(3S)\to\Upsilon(2S)+\gamma\gamma$, $\pi^0\pi^0$ and $\pi^+\pi^-$.

The inclusive events were detected using our normal hadronic trigger criteria. The exclusive events satisfied various combinations of these redundant triggers, depending on whether the daughter Υ decayed to e^+e^- or $\mu^+\mu^-$. The exclusive muon events satisfied the requirement of at least two tracks in the tracking chambers and at least two time-of-flight counters firing. The electron events could satisfy these trigger conditions, plus others which demanded a minimum energy in the shower counters.

To identify inclusive events from transitions (a), (b), and (c), we selected pairs of oppositely charged tracks in hadronic events by requiring that one track come within 6 mm of the event vertex in the plane perpendicular to the beam direction and the other within 18 mm. Pairs of tracks that were consistent with coming from photon conversion or the decay of a K^0 or Λ were removed.

Exclusive events from transitions (a) and (b) were selected by requiring two oppositely charged tracks with momenta greater than 3.5 GeV/c, and two oppositely charged tracks with momenta less than 0.75 GeV/c. We assumed that the high-momentum tracks were either e^+e^- or $\mu^+\mu^-$ pairs and the low-momentum tracks were $\pi^+\pi^-$. Monte Carlo studies indicate that the background from $\tau^+\tau^-$ events is negligible. Exclusive events from transition (c) were selected by allowing, in addition to the above criteria, at most two more charged tracks with momenta less than 0.75 GeV/c, to allow for the pions from the decay $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S)$. Track pairs that were consistent with originating from converted photons were removed from consideration. The low-momentum tracks had the same vertex constraints as used for the inclusive events. As a check on our ability to correctly identify very low-momentum pions, a subset of the exclusive $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S)$ candidate events were scanned separately by two physicists looking for track-finding mistakes. Less than 2% of the events were deemed to have come from this source. The lepton candidates were required to be within the fiducial volume of the time-of-flight counters [$|\cos(\theta)|<0.6$], in order to reliably calculate the trigger efficiency. For measuring the $\pi^+\pi^-$ invariant-mass spectra, we increased our data sample by removing this latter cut. We also included an additional 11 pb^{-1} of data from the second running period, for which the trigger configuration was changing and hence not easily modeled. It was possible to add these data for this aspect of the analysis since our trigger efficiency was independent of the $\pi^+\pi^-$ invariant mass.

III. RESULTS

A. $\pi^+\pi^-$ recoil-mass spectra and $\Upsilon(3S)$ branching ratios

The $\pi^+\pi^-$ recoil-mass spectrum for the four-track exclusive events is shown in Fig. 2 separately for data samples 1 and 2. The $\pi^+\pi^-$ recoil-mass rms resolution is about 5 to 8 MeV/c^2 (depending on recoil mass) for both data samples. There are three clear peaks in each data sample corresponding to the decays $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$, $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S)$, and $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$. The $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$ peak is necessarily offset from the correct $\Upsilon(1S)$ mass by approximately the $\Upsilon(3S)$ to $\Upsilon(2S)$ mass difference, because the pions were assumed to have come from the $\Upsilon(3S)$. The width of the $\Upsilon(2S)$ peak is dominated by the Doppler broadening due to the motion of the $\Upsilon(2S)$ in the laboratory frame, and the observed width is consistent with the expected value from Monte Carlo simulations.

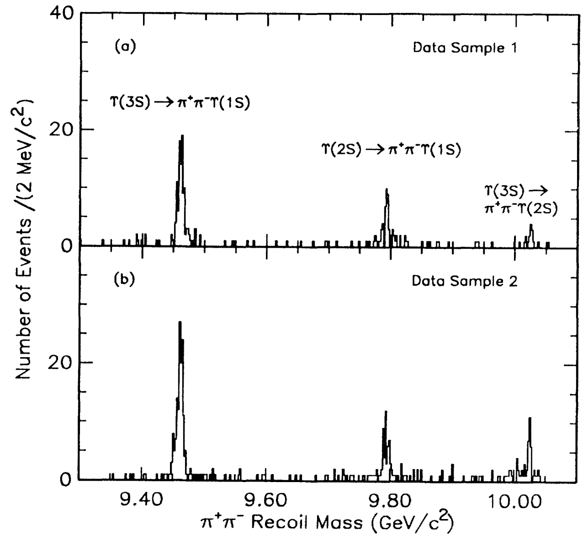

FIG. 2. The $\pi^+\pi^-$ recoil-mass spectrum for exclusive events from $\Upsilon(3S)\to\pi^+\pi^-X$ for (a) data sample 1, and (b) data sample 2. We note that the $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$ peak is offset from the correct $\Upsilon(1S)$ mass because the pions were assumed to have come from the $\Upsilon(3S)$.

As a check on the exclusive event sample, we identified the two high-momentum tracks as either e^+e^- or $\mu^+\mu^-$ using the information from the shower counters. As expected, we found equal numbers of electrons and muons within statistics for the transitions $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$ and $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$. The $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S)$ transition had a statistically significant excess of electron over muon events. However, there is more background under the $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S)$ recoil-mass peak than for the other two transitions, coming mainly from radiative Bhabha events. The excess of electron events was consistent with the estimate of the number of background events under the recoil-mass peak.

We fitted each of the three peaks to the sum of two bifurcated Gaussians[21] plus a flat background. This parametrization was found to fit best the corresponding peaks from a Monte Carlo simulation of the decays. The Monte Carlo events were generated with an isotropic angular production and decay of the $\pi^+\pi^-$ system, and produced such that they agree with our measured $\pi^+\pi^-$ invariant-mass spectra (see below). For each peak the ratios of the widths of the Gaussians were fixed to the values found from fitting the corresponding Monte Carlo–simulated recoil-mass spectrum. The overall widths of the Gaussians were left free in the fits, though, and their fitted values agreed well with the predictions from the Monte Carlo simulation.

In our earlier publication,[3] we used the sum of two symmetric Gaussians to fit the peaks. In both the case of two symmetric Gaussians and of two bifurcated Gaussians, one of the Gaussians was used to fit the narrow part of the recoil-mass peak, and the other was used to fit the tails. While the sum of two symmetric Gaussians gave almost as good a fit as the sum of two bifurcated Gaussians for the $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$ and $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$ transitions, the $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S)$ peak was much better fit with the new parametrization. This was true for both the Monte Carlo–simulated events and the data. This is due to the very low momentum of the pions from the $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S)$ transition, which causes an asymmetric tail in the $\pi^+\pi^-$ recoil-mass spectrum. We did check, though, that fitting both the exclusive and inclusive peaks to various other parametrizations, including two symmetric Gaussians and a Breit-Wigner form, did not change the final numbers of corrected events outside of the errors.

The inclusive $\pi^+\pi^-$ recoil-mass spectrum is shown in Fig. 3. Again, we show separately the results from data samples 1 and 2. Expansions of the regions around the peaks are shown in Figs. 4(a)–4(c). For Fig. 4(c) the $\pi^+\pi^-$ were assumed to originate from the $\Upsilon(2S)$ instead of the $\Upsilon(3S)$, which causes the resulting recoil-mass peak to be at the correct $\Upsilon(1S)$ mass. We fitted the inclusive peaks to the same shape as used for the exclusive events. Again, we used fits to Monte Carlo–simulated inclusive events to determine the relative widths of the Gaussians, but left the overall widths free. The background shape was parametrized by a Chebyshev polynomial. The results of the fits are shown by the curves in Fig. 4(a)–4(c). The numbers of events found from the fits for both the exclusive and inclusive modes are given in Table I. Systematic errors were estimated for the number of inclusive events by varying the form of the background fitting function. These systematic errors were less than 4% for the $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$ and $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$ transitions. However, they were substantially larger for the inclusive $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S)$ decay (21% for data sample 1 and 9% for data sample 2). This is because the recoil-mass peak for this mode is at the edge of phase space, and the the background is rapidly varying and difficult to fit. The statistical and systematic errors were added in quadrature to obtain the final errors on the number of events shown in Table I.

Our inclusive and exclusive detection efficiencies for the various decay modes, shown in Table I, were calculated from the Monte Carlo simulation of each transition. The errors on the efficiencies include a 2.5–5 % systematic error in the track-finding efficiency, depending on the decay mode. The exclusive decay mode efficiencies also include a 3% systematic error due to uncertainties in the trigger efficiency. An important assumption in the determination of the efficiencies for the exclusive decay modes is the angular distribution of the lepton pairs from the daughter Υ used in the Monte Carlo simulation. All theoretical models predict that the pions are dominantly in an S state, which leads to a $1+\cos^2(\theta)$ distribution for the leptons. However, other even^{++} states are allowed,

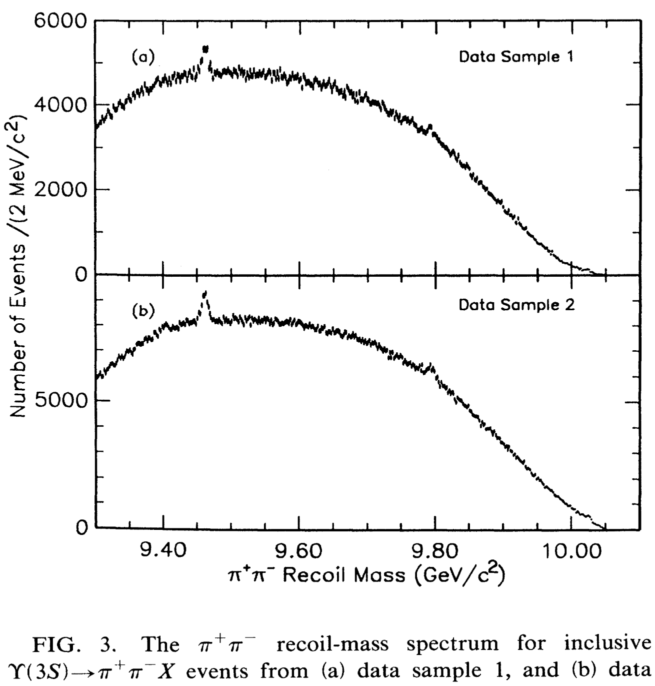

FIG. 3. The $\pi^+\pi^-$ recoil-mass spectrum for inclusive $\Upsilon(3S)\to\pi^+\pi^-X$ events from (a) data sample 1, and (b) data sample 2.

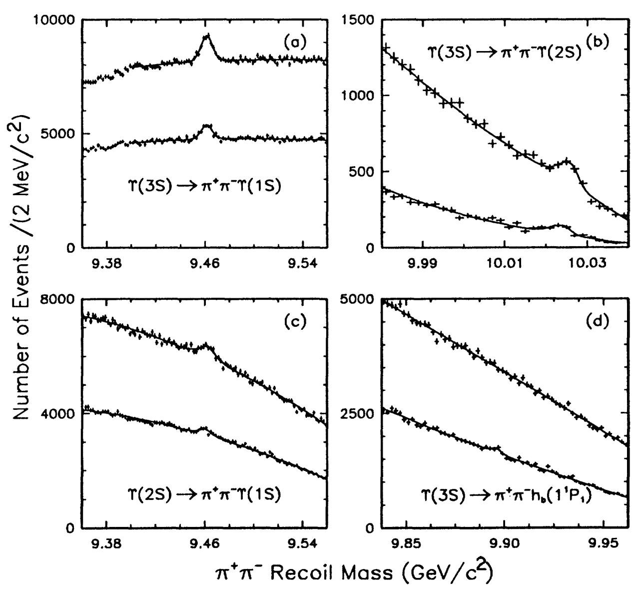

FIG. 4. The $\pi^+\pi^-$ recoil-mass spectrum for inclusive $\Upsilon(3S)\to\pi^+\pi^-X$ events in the region of (a) $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$, (b) $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S)$, (c) the cascade process $\Upsilon(3S)\to\Upsilon(2S)+X$, $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$ [for this figure, the $\pi^+\pi^-$ were assumed to originate from the $\Upsilon(2S)$], and (d) $\Upsilon(3S)\to\pi^+\pi^-h_b$. In each plot, the lower points are data sample 1, and the upper points are data sample 2. The curves are from fits described in the text.

which can produce a flatter angular distribution.[22] Our angular coverage is not large enough to distinguish between the various possible distributions. We, therefore, assumed an efficiency which was the average of that for the $1+\cos^2(\theta)$ and the isotropic angular distributions, and included as a systematic error the difference between this average efficiency and the two individual efficiencies. The final errors on the efficiencies were calculated by adding the statistical uncertainties from the Monte Carlo procedure in quadrature with the systematic errors.

The resulting branching fractions for the various $\Upsilon(3S)$ decay modes are given in Table I. To extract the branching ratios $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S), \Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S)$, and $\Upsilon(3S)\to\Upsilon(2S)+X$ from the exclusive events, we assumed e-μ universality and used the world-average branching ratios[17] for the decay of the $\Upsilon(1S)$ and $\Upsilon(2S)$ to muon pairs, $B_{\mu\mu}(1S)$ and $B_{\mu\mu}(2S)$, and for the decays $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$ and $\Upsilon(2S)\to\Upsilon(1S)+$neutrals. The latter consisted of the sum of $\Upsilon(2S)\to\Upsilon(1S)+\gamma\gamma$ and $\Upsilon(2S)\to\Upsilon(1S)+\pi^0\pi^0$. To obtain the $\Upsilon(3S)\to\Upsilon(2S)+X$ branching fraction from the inclusive results, we divided our measured product branching fraction by the world-average $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$ branching fraction.[17] The errors on the final branching ratios are the statistical and systematic uncertainties added in quadrature. The systematic errors include the uncertainties in the various world-average branching ratios, e.g., $B_{\mu\mu}(1S)$, used to calculate the final values. The agreement between the exclusive and inclusive measurements is reasonable. There is also good agreement between the measurements from the two data samples. Because the systematic errors on the exclusive mode efficiencies are correlated, we give in Table II the product branching ratios from combining the exclusive events for the two data sets. Also given in Table II are the average branching ratios for the inclusive and exclusive events separately, using the same assumptions as in Table I, and the final overall branching ratios from combining the inclusive and exclusive results.

If we subtract the $\Upsilon(3S)\to\pi\pi\Upsilon(2S)$ branching fraction [assuming $B(\Upsilon(3S)\to\pi^0\pi^0\Upsilon(2S))=\frac{1}{2}B(\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S))$] from our measured total $\Upsilon(3S)\to\Upsilon(2S)+X$ branching fraction, we obtain $(7.8\pm1.4)\%$ as the total branching fraction for all other transitions from the $\Upsilon(3S)$ to the $\Upsilon(2S)$. This branching fraction is consistent with the value measured directly by the CUSB Collaboration[23] for the photon transitions

TABLE I. Summary of results from data samples 1 and 2.

	Data sample 1, exclusive data	Data sample 2, exclusive data	Data sample 1, inclusive data	Data sample 2, inclusive data
$\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$				
Number of events	106 ± 11	145 ± 13	3770 ± 345	7200 ± 479
Efficiency (%)	31.5 ± 4.1	32.2 ± 4.5	51.0 ± 4.2	64.4 ± 4.7
$B(\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S))$ $\times 2B_{\mu\mu}(1S)^{a}$	$(2.13\pm0.36)\times10^{-3}$	$(1.90\pm0.32)\times10^{-3}$		
$B(\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S))$ (%)	4.15 ± 0.71^{b}	3.70 ± 0.63^{b}	4.69 ± 0.59	4.72 ± 0.48
$\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S)$				
Number of events	13.4 ± 5.0	28.0 ± 6.5	291 ± 94	642 ± 141
Efficiency (%)	8.0 ± 1.3	7.7 ± 1.3	9.0 ± 1.3	15.5 ± 2.6
$B(\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S))$ $\times[2B_{\mu\mu}(2S)^{a}$ $+B(\Upsilon(2S)\to\Upsilon(1S)+\text{neutrals}$ $\times 2B_{\mu\mu}(1S)^{a}]$	$(1.06\pm0.43)\times10^{-3}$	$(1.54\pm0.45)\times10^{-3}$		
$B(\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S))$ (%)	3.13 ± 1.36^{c}	4.54 ± 1.49^{c}	2.05 ± 0.72	1.75 ± 0.49
$\Upsilon(3S)\to\Upsilon(2S)+X$, $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$				
Number of events	52.0 ± 9.2	69.5 ± 9.1	1310 ± 327	3460 ± 552
Efficiency (%)	29.2 ± 3.8	30.7 ± 4.1	50.9 ± 4.2	56.5 ± 4.5
$B(\Upsilon(3S)\to\Upsilon(2S)+X)$ $\times B(\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S))$ $\times 2B_{\mu\mu}(1S)^{a}$	$(1.13\pm0.25)\times10^{-3}$	$(0.95\pm0.18)\times10^{-3}$		
$B(\Upsilon(3S)\to\Upsilon(2S)+X)$ $\times B(\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S))$			$(1.64\pm0.43)\times10^{-2}$	$(2.59\pm0.47)\times10^{-2}$
$B(\Upsilon(3S)\to\Upsilon(2S)+X)$ (%)	$11.9\pm2.7^{b,d}$	$10.0\pm2.0^{b,d}$	8.8 ± 2.4^{d}	14.0 ± 2.6^{d}

[a]With the assumption of e-μ universality.
[b]By use of the world average $B_{\mu\mu}(1S)=(2.57\pm0.07)\%$ from Ref. 17.
[c]By use of $B_{\mu\mu}(2S)=(1.37\pm0.26)\%, B(\Upsilon(2S)\to\gamma\gamma\Upsilon(1S))\times2B_{\mu\mu}(1S)=(0.195\pm0.036)\%$ (see footnote a), and $B(\Upsilon(2S)\to\pi^0\pi^0\Upsilon(1S))\times2B_{\mu\mu}(1S)=(0.452\pm0.058)\%$ (see footnote a) from Ref. 17.
[d]By use of the world average $B(\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S))=(18.5\pm0.8)\%$ from Ref. 17.

TABLE II. The average exclusive and inclusive branching ratios from combining data samples 1 and 2, and the overall branching ratios from combining the inclusive and exclusive events.

	Average of exclusive results, data samples 1 and 2	Average of inclusive results, data samples 1 and 2	Average of data samples 1 and 2
$B(\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S))$ $\times 2B_{\mu\mu}(1S)$	$(2.00\pm0.29)\times10^{-3}$		
$B(\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S))$ $\times[2B_{\mu\mu}(2S)$ $+B(\Upsilon(2S)\to\Upsilon(1S)+\text{neutrals})$ $\times 2B_{\mu\mu}(1S)]$	$(1.30\pm0.33)\times10^{-3}$		
$B(\Upsilon(3S)\to\Upsilon(2S)+X)$ $\times B(\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S))$ $\times 2B_{\mu\mu}(1S)$	$(1.01\pm0.17)\times10^{-3}$		
$B(\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S))$ (%)	3.90 ± 0.58	4.71 ± 0.37	4.47 ± 0.31
$B(\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S))$ (%)	3.84 ± 1.14	1.84 ± 0.41	2.07 ± 0.38
$B(\Upsilon(3S)\to\Upsilon(2S)+X)$ (%)	10.6 ± 1.8	11.2 ± 1.7	10.9 ± 1.3

from the $\Upsilon(3S)$ to the $\Upsilon(2S)$ via the intermediate $\chi_b(2\,^3P_J)$ states. However, given the errors on both measurements, we cannot rule out the existence of other transitions between the $\Upsilon(3S)$ and $\Upsilon(2S)$.

B. Search for the h_b and other transitions

We have also used the inclusive $\pi^+\pi^-$ recoil-mass spectrum to look for other possible $\pi^+\pi^-$ transitions. In particular, we are sensitive to the production of the $h_b(1\,^1P_1)$ state through the decay $\Upsilon(3S)\to\pi^+\pi^-h_b$ (see Fig. 1). The h_b resonance has not previously been observed, but its mass is expected to be close to the center of gravity of the three χ_b states at 9900.2 ± 0.7 MeV/c^2.[17] An accurate measurement of the mass difference between the h_b and the χ_b center of gravity gives information on the spin-spin coupling in the $b\bar{b}$ system.[24] Some theoretical models predict the $\Upsilon(3S)\to\pi^+\pi^-h_b$ transition to have a branching ratio in the range 0.1% to 1%,[25] while others[26] give a value less than 0.01%. (For a comparison of the predictions on the branching ratio, see Kuang, Tuan, and Yan.[25])

The $\pi^+\pi^-$ recoil-mass spectrum in this mass region is shown in Fig. 4(d) separately for the two data samples. We searched for the h_b fitting the recoil-mass spectrum in the region of 9900 MeV/c^2 to a signal shape which was similar to that used for the three Υ inclusive transitions, plus a Chebyshev polynomial for the background. The signal shape was confirmed by a Monte Carlo simulation of h_b production. The largest fluctuation found in data sample 1,[3] was an excess of 280 ± 100 events[27] at a mass of 9894.8 ± 1.5 MeV/c^2. Given the increase in integrated luminosity between data samples 1 and 2, and an estimated 30% increase in detection efficiency found from the Monte Carlo simulations, we would expect 544 ± 205 events in data sample 2. The fit at this mass in data sample 2 gives -5 ± 140 events. The fits to the data samples for this mass are shown by the curves in Fig. 4(d). With these statistics, we cannot confirm the existence of the h_b. Combining data samples 1 and 2, the 90%-confidence-level upper limit on the branching ratio for the transition $\Upsilon(3S)\to\pi^+\pi^-h_b$ is 0.31% for an h_b mass of 9894.8 MeV/c^2, and 0.15% for a mass at the χ_b center of gravity.

Another possible $\pi^+\pi^-$ transition in the Υ system is the decay $\Upsilon_J(1\,^3D)\to\pi^+\pi^-\Upsilon(1S)$, with $J=1$, 2, and 3 (see Fig. 1). The three D states can be produced by photon transitions from the $\Upsilon(3S)$ through the $\chi_b(2\,^3P)$ states. Theoretical predictions[28] for the sum of the product branching ratios $B(\Upsilon(3S)\to\gamma\chi_b(2\,^3P))B(\chi_b(2\,^3P)\to\gamma\Upsilon(1\,^3D))$ over all possible transitions are on the order of 0.5%. Various theoretical calculations of the $\Upsilon(1\,^3D)\to\pi^+\pi^-\Upsilon(1S)$ branching ratio differ by an order of magnitude,[12,29] though the most recent ones give a small value of around 0.25% for each of the three D states.

We have searched for the $1\,^3D$ states in a manner similar to the h_b, by using the inclusive $\pi^+\pi^-$ recoil-mass spectrum. The three $1\,^3D$ states are expected to have a center of mass around 10.156 GeV/c^2, with a mass splitting of about 5 MeV/c^2.[28] These predictions are very insensitive to the various theoretical inputs. Since the D states are not produced directly, though, the position of their peaks in the $\pi^+\pi^-$ recoil-mass spectrum due to their decay to the $\Upsilon(1S)$ should be shifted to around 9.66 GeV/c^2. We have searched for such transitions over the recoil-mass range from 9.64 to 9.68 GeV/c^2. Our rms resolution in recoil mass for this mass range is 5 MeV/c^2, which is comparable to the expected splitting between the D states. We therefore conducted the search for the D states in smaller steps of 2 MeV/c^2. At each step in recoil mass, we fitted the measured distribution to a peak plus a smooth background. Taking the largest fluctuation from these fits, we obtain a 90%-confidence-level upper limit on the product branching ratio $B(\Upsilon(3S)\to\Upsilon(1\,^3D)+X)B(\Upsilon(1\,^3D)\to\pi^+\pi^-\Upsilon(1S))$ of 0.6% for any of the three D states.

We have also searched for the exclusive decay $\Upsilon(3S)\to\eta\Upsilon(1S)$, with the η decaying into $\pi^+\pi^-\pi^0$. There are no previous upper limits on this branching ratio. Theoretical predictions for the branching fraction vary by several orders of magnitude.[12] Voloshin and Zakharov[13] predict a ratio for $B(\Upsilon(3S)\rightarrow\eta\Upsilon(1S))/B(\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(1S))$ of about 0.02, which corresponds to a $B(\Upsilon(3S)\rightarrow\eta\Upsilon(1S))$ of around 0.09%. To search for this decay mode, we kinematically fitted our exclusive four-prong events in data sample 2 under the assumption that the two leptons were from $\Upsilon(1S)$ decay, and that there was a missing π^0 which, along with the measured $\pi^+\pi^-$, gave an invariant mass consistent with an η. We found no events consistent with this hypothesis. Our efficiency for detecting this decay chain is 26%, as determined by Monte Carlo simulation. From this search, we set a 90%-confidence-level upper limit on the branching fraction for $\Upsilon(3S)\rightarrow\eta\Upsilon(1S)$ of 0.22%.

C. $\pi^+\pi^-$ invariant-mass spectra

1. Measured spectra

The $\pi^+\pi^-$ invariant-mass spectra for the exclusive decay modes $\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(1S)$ and $\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(2S)$ are shown as the circular data points in Figs. 5(a) and 5(b) for data samples 1 and 2 combined. No background has been subtracted for these points, since the relative fraction of background in the exclusive events is very small. The rms resolution in $\pi^+\pi^-$ invariant mass is about 7 MeV/c^2 for both data sets. Except for the lowest invariant-mass bin just above threshold in the $\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(1S)$ plot, our efficiencies are constant as a function of $\pi^+\pi^-$ invariant mass. This one invariant-mass bin has been corrected by a relative efficiency compared to the other bins of 0.63 (0.72) for data sample 1 (2), as determined by a Monte Carlo simulation of the efficiencies.

For the inclusive events, the data were divided into bins of $\pi^+\pi^-$ invariant mass, and the recoil-mass distributions for each bin were fit using the overall recoil-mass means and widths determined from fitting the entire spectrum. Fixing the width substantially reduced the error on the number of events obtained from the inclusive fits, especially in the case of the $\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(2S)$ transition, in which the signal is small and the background is changing rapidly. This is a reasonable procedure since we are only concerned here with the relative shape of the distributions as a function of invariant mass. We checked, though, that if we allowed the mass and width to vary that there was no dependence on them as a function of invariant mass in fitting the peaks. This was also confirmed by Monte Carlo simulation. Our efficiency for the inclusive events is constant as a function of $\pi^+\pi^-$ invariant mass, as found from Monte Carlo–generated events. However, we added a systematic error on the number of events in each invariant-mass bin of from 8% to 17%, depending on the decay mode, to account for possible variations in the efficiency. We also included an additional systematic error on each point found by changing the background fitting function and the recoil-mass range over which the fit was done. The statistical and systematic errors were then added in quadrature. The resulting inclusive dipion invariant-mass spectra for the two transitions are shown in Figs. 5(a) and 5(b) as the square data points. For both transitions there is good agreement between the inclusive and exclusive results, and also between the two data samples. With the addition of data sample 2, the $\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(1S)$ spectrum now shows a statistically significant number of events immediately above threshold. The $\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(2S)$ exclusive spectrum is also much improved in statistics in comparison with our previous results.[3] Furthermore, this is the first time we have been able to measure the $\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(2S)$ spectrum using the inclusive events. Like the $\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(1S)$ distribution, both the inclusive and exclusive $\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(2S)$ spectra also appear to have a significant component of low-mass events.

The $\pi^+\pi^-$ invariant-mass spectrum we find in $\Upsilon(3S)$ decays for the transition $\Upsilon(2S)\rightarrow\pi^+\pi^-\Upsilon(1S)$ is shown in Fig. 5(c) for both the inclusive and exclusive events. These spectra were obtained using an identical procedure to that used for the $\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(1S)$ and $\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(2S)$ transitions. The distributions agree

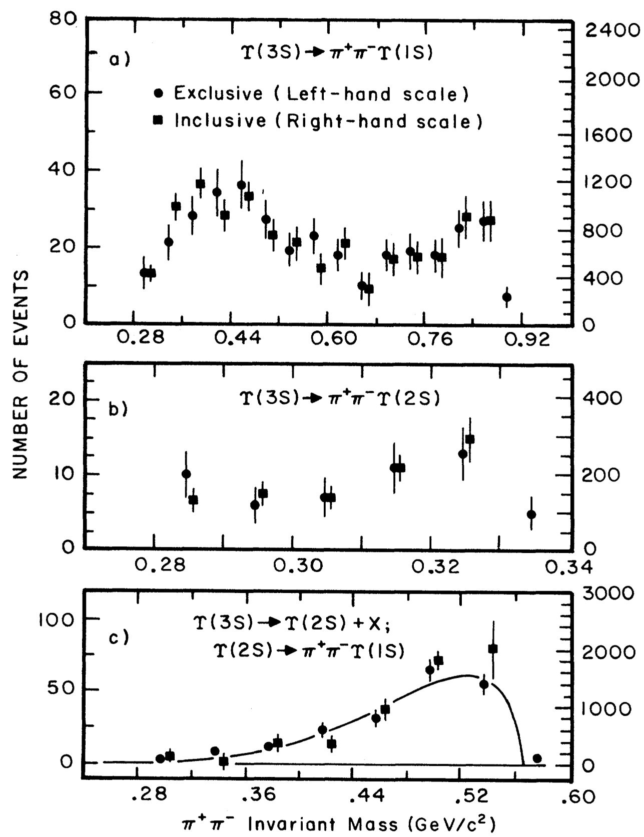

FIG. 5. The $\pi^+\pi^-$ invariant-mass spectrum for the transitions (a) $\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(1S)$, (b) $\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(2S)$, and (c) $\Upsilon(2S)\rightarrow\pi^+\pi^-\Upsilon(1S)$ found in $\Upsilon(3S)$ decay. Data samples 1 and 2 are combined. The exclusive events are shown by the circular data points (use the left-hand scale), and the inclusive events are represented by the square data points (use the right-hand scale). The inclusive and exclusive points in each bin have been slightly offset from each other for clarity. The curve in (c) is a fit using data taken at the $\Upsilon(2S)$ from Ref. 3 to the prediction of the Yan model (Ref. 12).

well with our previous measurement[7] made at the $\Upsilon(2S)$. This is shown by the curve in Fig. 5(c), which is a fit using our previous $\Upsilon(2S)$ data to the Yan model prediction.[12] This agreement demonstrates the validity of our method and also emphasizes the large difference between the $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$ invariant-mass distribution and the two corresponding spectra from the $\Upsilon(3S)$, displayed in Figs. 5(a) and 5(b).

2. General comments

As discussed in our previous publication,[3] we could not obtain a reasonable fit to the $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$ spectrum using the models of Yan,[12] Voloshin and Zakharov[13] or Novikov and Schifman,[14] all of which describe the $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$ and $\psi'\to\pi^+\pi^-(J/\psi)$ spectra well. Nor could we fit the model of Peskin[30] or a simple phase-space model. This is still the case with the addition of the new data. None of these models provides a reasonable description of the $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$ invariant-mass spectrum. The confidence levels of all the fits are below 1%.

A possible explanation for the failure of the theoretical predictions for the $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$ spectrum could be that the available phase space has become so large that the assumptions used in the soft-pion approximation have broken down. However, the Q value for the decay $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S)$ is even smaller than that for $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$, where the theories are successful. Therefore, the $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S)$ spectrum would seem to be a ideal place to further test these models. With the improvement in our data, we are able to do this for both the inclusive and exclusive cases. Surprisingly, we find that none of the models describe well the $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S)$ spectrum shown in Fig. 5(b). For example, the fit to the Yan model[12] has a confidence level of only 4%. The fits to the other models give similar results. Our measured $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S)$ spectrum would seem, therefore, to disagree with these theoretical predictions.

In a paper by Bélanger, DeGrand, and Moxhay,[31] modifications to the $\pi^+\pi^-$ invariant-mass distributions due to corrections in the multipole expansion and to final-state $\pi^+\pi^-$ interactions were studied. They found that these effects were not large enough to account for the discrepancy between the theoretical predictions and our data.

3. Possibility of a $\pi^+\pi^-$ resonance

The disagreement between the data and the theoretical predictions for the $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$ and $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S)$ distributions is mainly due to the excess of low-mass events in both spectra. This enhancement in the spectra near threshold suggests the possibility of resonance production at low $\pi^+\pi^-$ invariant mass. The high-mass part of the two spectra could then be explained by the usual QCD models. The quantum numbers of such a resonance would have to be 0^{++}, 2^{++}, etc. To test the 0^{++} resonance hypothesis, we fitted simultaneously the inclusive and exclusive spectra from our $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$ and $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S)$ data, along with our previously measured $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$ spectra,[7] to an S-wave Breit-Wigner form weighted by phase space plus the Yan-model form.[12] In contrast to the other fits, the confidence level for this fit is acceptable (24%). The fitted values for the mass and width of the Breit-Wigner form are 350±10 MeV/c^2 and 240±20 MeV/c^2, respectively. There is good agreement between the fitted values obtained separately from the inclusive and exclusive spectra. The fraction of the total spectrum under the Breit-Wigner form is 0.7 in the $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$ data and about 0.5 in the $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S)$, while in the $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$ it is only 0.04. These relative fractions are reasonable, though, since the partial width for $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$ is much larger than that for $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$ or $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S)$, and the phase space available for the decay of the $\Upsilon(2S)$ to such a resonance would be smaller than that for the $\Upsilon(3S)$, thus further suppressing the branching ratio. However, the confidence level for the fit to the $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S)$ spectrum is poor (2%), since neither the phase-space-weighted Breit-Wigner form nor the Yan-model form rises fast enough to fit the lowest invariant-mass data point.

We have also investigated the possibility of higher-spin $\pi\pi$ resonances by measuring the angle $\theta_{\pi\pi}$ of the $\pi^+\pi^-$ system with respect to the beam direction. This angular distribution is sensitive to the production mechanism of the $\pi^+\pi^-$. The $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$ inclusive and exclusive events were divided into a low-mass band ($m_{\pi\pi}<0.64$ GeV/c^2) and a high-mass band ($m_{\pi\pi}>0.64$ GeV/c^2). In all cases, we compared the data with our Monte Carlo events generated assuming isotropic production and decay of the $\pi^+\pi^-$ system. In Figs. 6(a) and 6(b), we see good agreement between the data (points with error bars) and the Monte Carlo simulation (line). The confidence levels found from fitting the data to the Monte Carlo curves are 20% and 57% for the low- and high-mass bands, respectively.

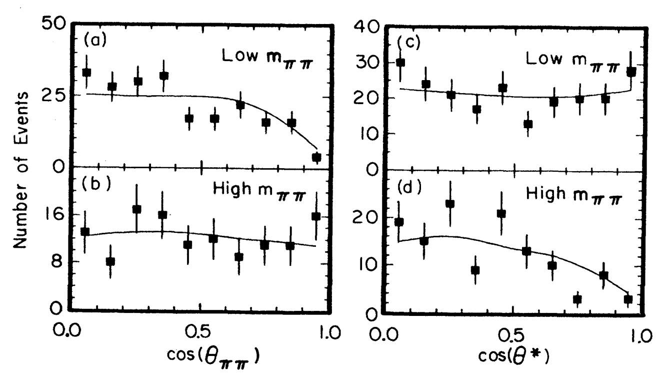

FIG. 6. Angular distributions from the inclusive and exclusive decays of $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$. The angle $\theta_{\pi\pi}$ is the angle between the $\pi^+\pi^-$ system and the beam direction, while θ^* is the angle between the π^+ and the beam direction in the $\pi^+\pi^-$ rest frame. (a) and (c) are for $m_{\pi\pi}<0.64$ GeV/c^2, while (b) and (d) are for $m_{\pi\pi}>0.64$ GeV/c^2. The curves are from a Monte Carlo simulation assuming the isotropic production and decay of the $\pi^+\pi^-$ system.

To look at the decay mechanism of the $\pi^+\pi^-$ system, we measured the angle θ^* of the π^+ with respect to the beam direction in the $\pi^+\pi^-$ rest frame for the two $\pi^+\pi^-$ mass regions [see Figs. 6(c) and 6(d)]. Again, the data and the Monte Carlo predictions are in reasonable agreement (the confidence levels are 58% and 7%, respectively). The low-mass data are, therefore, completely consistent with the isotropic production and decay of the $\pi^+\pi^-$ system. While this does not rule out the possibility of a higher-spin resonance, to do so would require explicit predictions for the various density-matrix elements in the decay of such a resonance.

While the postulation of a $\pi\pi$ resonance can provide an acceptable fit to the two $\Upsilon(3S)$ spectra, a paper by Morgan and Pennington[32] showed that such an explanation has unacceptable consequences. They argued that any resonance in the $I=J=0$ $\pi\pi$ channel automatically affects the $\pi\pi\to\pi\pi$ elastic-scattering channel also, and forces the cross section for this process to reach almost the unitarity limit. This disagrees with many experimental data. The same argument also holds for any higher-spin $\pi\pi$ resonance. This would seem to rule out the possibility that our acceptable fit using a simple Breit-Wigner shape could be evidence for a $\pi\pi$ resonance.

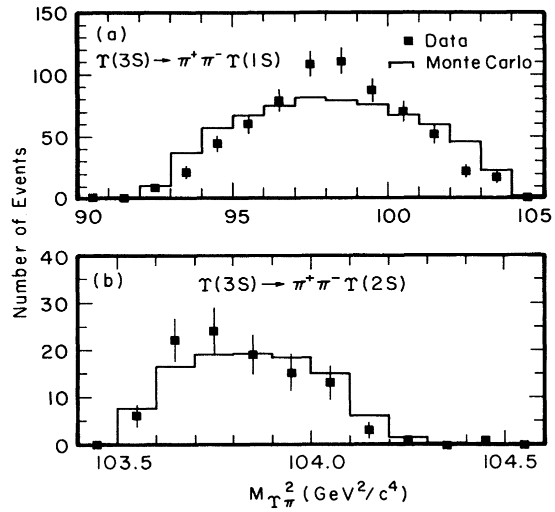

FIG. 7. The $\Upsilon\pi$ invariant-mass spectra for (a) exclusive $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$ and (b) exclusive $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S)$ events (points with error bars). Data samples 1 and 2 are combined. Also shown are the predictions from the isotropic Monte Carlo events (histograms).

4. *Possibility of an $\Upsilon\pi$ resonance*

Voloshin[33] has suggested that the unusual $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$ spectrum could be due to a narrow four-quark isovector $\Upsilon\pi$ resonance, whose mass is between the $\Upsilon(2S)$ and $\Upsilon(3S)$. Such a state would then modify the $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$ spectrum without markedly affecting the corresponding $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$ spectrum. Bélanger, DeGrand, and Moxhay[31] have shown that choosing, for example, an $\Upsilon\pi$ resonance with a mass of 10.213 GeV/c^2 and a width of 10 MeV/c^2 can indeed produce a double-peaked shape in the $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$ spectrum. The existence of such a resonance is of great importance since it would be the first clear observation of a $q\bar{q}q\bar{q}$ state.

We have searched for such a state by measuring the $\Upsilon\pi$ invariant-mass distribution for the $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$ and $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S)$ exclusive events. These are shown in Fig. 7, along with the isotropic Monte Carlo predictions. An $\Upsilon\pi$ resonance which could explain the $\pi^+\pi^-$ invariant-mass distribution would appear as an excess of events at very low and high $\Upsilon\pi$ invariant masses. We see no evidence for such a state. It is interesting, though, that the $\Upsilon\pi$ invariant-mass distribution for $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$ does not agree well with the isotropic Monte Carlo simulation. This may point to some other dynamics in the decay. The Dalitz plots for our $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$ and $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S)$ exclusive events, along with the corresponding plots for the isotropic Monte Carlo events, are displayed in Figs. 8 and 9, respectively. Again, there is no evidence for any narrow $\Upsilon\pi$ resonance structure in either figure.

5. *Possibility of decay to a virtual $B\bar{B}$ pair*

An entirely different explanation of the $\pi^+\pi^-$ invariant-mass spectrum from the $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$ decay has been suggested by Lipkin and Tuan.[34] In their model, the $\Upsilon(3S)$ decays to a virtual $B\bar{B}$ pair, where one of the B's emits a π and decays to a B^*. The B^* then emits another π and decays to either a B or B^*. Angular momentum conservation requires that if the B^* decays to

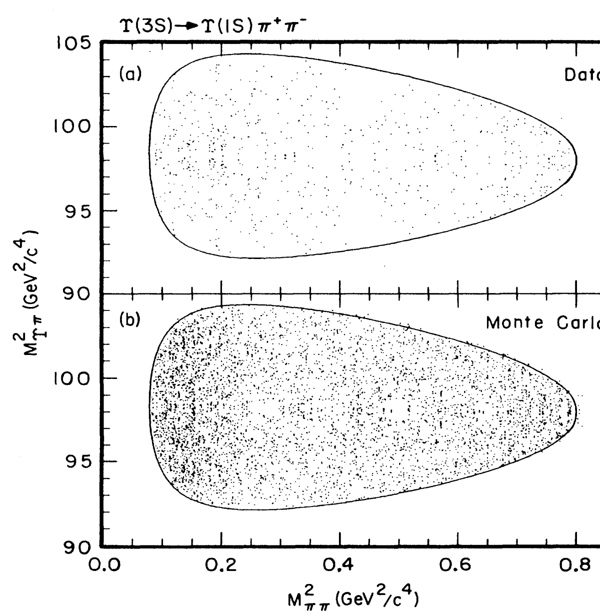

FIG. 8. (a) The Dalitz plot for the exclusive $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$ events. Data samples 1 and 2 are combined. (b) The corresponding Dalitz plot from the isotropic Monte Carlo events.

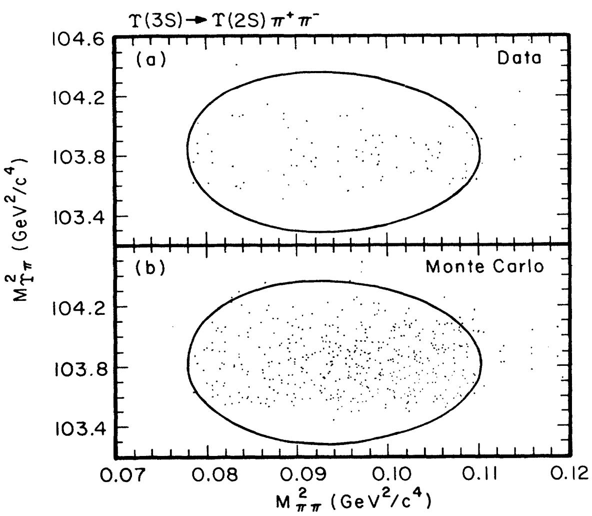

FIG. 9. (a) The Dalitz plot for the exclusive $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S)$ events. Data samples 1 and 2 are combined. (b) The corresponding Dalitz plot from the isotropic Monte Carlo events.

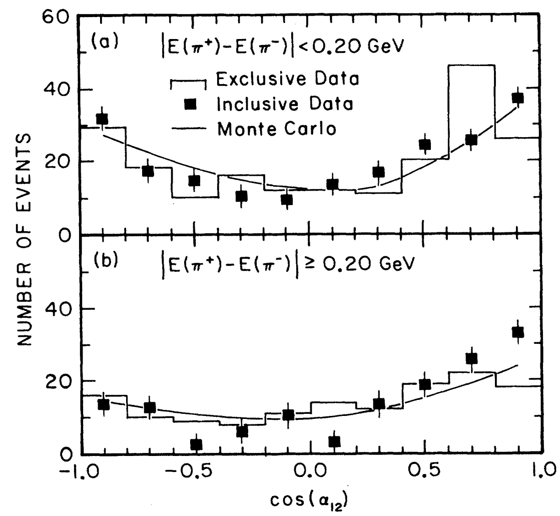

FIG. 10. The $\cos(\alpha_{12})$ distributions for inclusive and exclusive $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$ events, where α_{12} is the angle between the two pions. The inclusive data have been normalized to the total number of exclusive events. The distribution for similar $\pi^+\pi^-$ energies $[|E(\pi^+)-E(\pi^-)|<0.2$ GeV] is shown in (a), while that for dissimilar energies $[|E(\pi^+)-E(\pi^-)|>0.2$ GeV] is given in (b). The curves are from a Monte Carlo simulation assuming the isotropic production and decay of the $\pi^+\pi^-$ system.

a B, the angle between the two pions (α_{12}) has the form $\cos^2(\alpha_{12})$. If it decays to a B^*, though, the angular distribution is $\sin^2(\alpha_{12})$. The amplitudes for these processes would be very dependent on how close the mass of the Υ state is to $B\bar{B}$ threshold, thus explaining why the $\Upsilon(3S)\pi^+\pi^-$ spectrum could be affected but not the $\Upsilon(2S)$. To test this model, Lipkin and Tuan note that when the two pions have the same energy, wave function symmetry forbids the formation of two virtual B^*'s, so the $\cos^2(\alpha_{12})$ form should dominate. This form naturally produces a $\pi^+\pi^-$ invariant-mass spectrum which has both a low-mass and a high-mass peak, consistent with our measured distribution. When the two pions have dissimilar energies, both the $\cos^2(\alpha_{12})$ and the $\sin^2(\alpha_{12})$ forms should be present, producing a rather flat angular distribution.

The $\cos(\alpha_{12})$ distribution from our inclusive and exclusive $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$ events are shown in Figs. 10(a) and 10(b) for the two cases: (a) similar pion energies $[|E(\pi^+)-E(\pi^-)|<0.2$ GeV] and (b) dissimilar pion energies $[|E(\pi^+)-E(\pi^-)|>0.2$ GeV]. If we fit the distributions to the form $A\sin^2(\alpha_{12})+B\cos^2(\alpha_{12})$, we find $A/B\simeq1/3$ for both (a) and (b), with a very poor confidence level ($<1\%$) in each case. These results are inconsistent with the Lipkin-Tuan predictions that for (a) $A=0$ and for (b) $A\simeq B$. If we compare the measured angular distributions to the predictions from our isotropic Monte Carlo simulation (the curves in Fig. 10), we see that there is good agreement. In this case, there is little difference between the predictions for similar and dissimilar pion energies. From the Monte Carlo curves in Fig. 10 we see that having an angular distribution which peaks forward and backward is a feature of having a $\pi^+\pi^-$ invariant-mass distribution that peaks at low and high masses, and is not specific to the Lipkin-Tuan model.

Moxhay[35] has considered the possibility of interference between the Lipkin-Tuan process and the standard Yan-type model process. By making reasonable assumptions, he showed that the two processes could be of similar magnitude. By assuming the simplest parametrization for the Lipkin-Tuan amplitude, he was able to fit our double-peaked $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$ invariant-mass distribution. However, there is little motivation for this choice of parametrization, for the values of the parameters obtained from the fit, or for the dependence of these parameters on the masses of the Υ states involved. At present, Moxhay's procedure simply adds two free parameters to the fit of the $\pi^+\pi^-$ spectra. This result, though, does amplify the importance of understanding more completely the parameters of the Lipkin-Tuan model. In particular, a complete coupled-channel calculation which predicts the $\pi^+\pi^-$ invariant-mass spectra for the three transitions would be very desirable.

IV. CONCLUSION

In conclusion, we have measured with higher precision several of the branching ratios for $\pi^+\pi^-$ transitions in $\Upsilon(3S)$ decay. We have also improved the measurement of the inclusive branching ratio for $\Upsilon(3S)\to\Upsilon(2S)+X$, and found the first upper limit on the branching ratio for the exclusive $\Upsilon(3S)\to\eta\Upsilon(1S)$.

We have searched for the production of the $h_b(1P_1)$ in $\pi^+\pi^-$ transitions from the $\Upsilon(3S)$. We see no definitive evidence for the h_b resonance, and set a 90%-confidence-level upper limit on the branching ratio for $\Upsilon(3S)\to\pi^+\pi^-h_b$ of 0.15% for an h_b with a mass at the χ_b center of gravity. We also have set the first upper limit on the product branching ratio $B(\Upsilon(3S) \rightarrow \Upsilon(1\,^3D)+X)B(\Upsilon(1\,^3D)\rightarrow\pi^+\pi^-\Upsilon(1S))$ of 0.6% for any of the three D states.

We have measured with higher statistics the $\pi^+\pi^-$ invariant-mass distributions for the transitions $\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(1S)$ and $\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(2S)$ in both the exclusive and inclusive modes. The spectrum from the $\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(1S)$ decay has a significant number of events immediately above threshold, in sharp contrast to the spectrum in $\Upsilon(2S)\rightarrow\pi^+\pi^-\Upsilon(1S)$ decay. We cannot fit this distribution to any of the known QCD-inspired models. A similar situation is found for the $\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(2S)$ spectrum, for which the models were believed to be more reliable. We can obtain a reasonable fit to all the spectra by adding a phase space weighted Breit-Wigner form with a mass and width of ~ 300 MeV/c^2 to the Yan-model form. However, the individual fit of this parametrization to our $\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(2S)$ spectrum is poor. Furthermore, if this resonance is real, it leads to disagreements with data on $\pi\pi\rightarrow\pi\pi$ elastic scattering.[32] There is no evidence for the production of any higher-spin $\pi^+\pi^-$ resonance or for the existence of any narrow $\Upsilon\pi$ resonance.

Our $\pi^+\pi^-$ angular distributions are inconsistent with the predictions of the model of Lipkin and Tuan.[34] The possibility of interference[35] between the amplitudes of the Lipkin-Tuan model and the standard Yan-type models needs to be explored further before definite predictions can be made. It is, therefore, fair to say that at this time there is no theoretical explanation for the measured $\pi^+\pi^-$ invariant-mass distributions from $\Upsilon(3S)$ decay.

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