CLEO-CONF 05-01
LP2005-439

Decay of the $\psi(3770)$ to Light Hadrons*

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(Dated: June 29, 2005)

Abstract

We describe an analysis of light hadronic non-$D\bar{D}$ decays of the $\psi(3770)$. The vector-pseudoscalar final states $\rho^0\pi^0$, $\rho^+\pi^-$, $\omega\pi^0$, $\phi\pi^0$, $\rho\eta$, $\omega\eta$, $\phi\eta$, $\rho\eta'$, $\omega\eta'$, $\phi\eta'$, $K^{*0}\overline{K^0}$, and $K^{*+}K^-$are studied along with $b_1\pi$ and $\pi^+\pi^-\pi^0$. We find agreement with the expected yield from scaled continuum and other backgrounds, with the notable exceptions of a statistically significant signal for $\phi\eta$ and a suggestive suppression of $\pi^+\pi^-\pi^0$, $\rho\pi$, and $K^{*+}K^-$. We conclude with a form factor determination for $\omega\pi^0$, $\rho\eta$, and $\rho\eta'$. All results are preliminary.

*Submitted to the XXII International Symposium on Lepton and Photon Interactions at High Energies, June 30-July 5, Uppsala, Sweden

The $\psi(3770)$ charmonium state decays most copiously into the OZI allowed $D\bar{D}$ pair owing to the closeness of the mass threshold. Transitions to lower-lying charmonium state under emission of hadrons or a photon, decay to lepton pairs, or decay to light hadrons are available, but highly suppressed. An unresolved question is: By how much?

The cross-section $\sigma^{obs}(\psi(3770) \to D\bar{D})$ has been reported as $(6.14 \pm 0.12 \pm 0.50)$ nb (BES [1]) and $(6.39 \pm 0.10^{+0.17}_{-0.10})$ nb (CLEO [2]) recently. In the absence of an equally modern measurement of the hadronic decay cross-section, we use an average over older measurements of (7.9 ± 0.6) nb [3] to note a gap of around (1.5 ± 0.6) nb for non-$D\bar{D}$ decays.

BES reported the first sighting of a $\psi(3770)$ non-$D\bar{D}$ decay [4] at 3σ significance, with $\mathcal{B}(\psi(3770) \to \pi^+\pi^- J/\psi) = (0.34 \pm 0.14 \pm 0.09)\%$ using $28\,\mathrm{pb}^{-1}$ of e^+e^- collision data taken at center-of-mass energies around $\sqrt{s} = 3.773$ GeV. In the meantime, CLEO has accumulated much more data, so it is warranted to address this issue again. This is especially true in the context of modes suppressed on the $\psi(2S)$ in combination with the S/D mixing scenario. This model [5] argues that the mass eigenstates $\psi(2S)$ and $\psi(3770)$ could be mixtures of the 1^3D_1 and 2^3S_1 states of charmonium linked by a mixing angle θ, which is evaluated from other experimental data to be $(12 \pm 2)^\circ$. It is offered as a solution to the "$\rho\pi$ puzzle", stating that if the mixing angle is such that $\psi(2S) \to \rho\pi$ is suppressed, the corresponding $\psi(3770)$ width would be enhanced. (Given the large total width of the $\psi(3770)$, the resulting branching fractions will still be small.) Another effect that needs to be taken into account is interference with continuum. The continuum cross-sections are in the picobarn range. With $\psi(3770)$ decay cross-sections of similar magnitude, interference can result in a sizeable modification to the rate. This depends strongly on the assumed relative phase between the three contributing mechanisms, $c\bar{c} \to ggg$ (resonant strong), $c\bar{c} \to \gamma^*$ (resonant electromagnetic), and $e^+e^- \to \gamma^*$ (continuum). A non-zero $\psi(3770)$ width for a particular mode can thus result in a depression of the observed cross-section relative to that of continuum at energies close to $m(\psi(3770))$ [6].

This note describes the search for $\psi(3770)$ decay to vector meson pseudoscalar (VP) final states ($\rho^0\pi^0$, $\rho^+\pi^-$, $\omega\pi^0$, $\rho\eta$, $\omega\eta$, $\phi\eta$, $\rho\eta'$, $\omega\eta'$, $\phi\eta'$), with the addition of the $\pi^+\pi^-\pi^0$ final state and $b_1\pi$ as the most copiously produced two-body $\psi(2S)$ final state, in CLEO-c data taken at the $\psi(3770)$ resonance. We use two data samples: $281\,\mathrm{pb}^{-1}$ of data taken at $\sqrt{s} = 3.773$ GeV ("$\psi(3770)$ sample") and $21\,\mathrm{pb}^{-1}$ taken at $\sqrt{s} = 3.67$ GeV ("continuum data"). We establish event yields in the $\psi(3770)$ sample by counting events that fulfill the selection criteria detailed below and subtracting misreconstructed candidates. The same is done for the continuum sample. As an experimentally unambiguous quantity, we measure the visible cross-section for all modes and arrive at an upper limit for the sum. The sideband subtracted $\psi(3770)$ sample event numbers are compared with with the expected background from continuum, determined in two ways, in order to discern a statistically significant discrepancy between the two. Measurement of the continuum cross-section gives access to the form factor, assuming the cross-section is given by

$$\sigma(s) \sim \frac{1}{s}|\mathcal{F}(s)|^2 q^3_{VP}(s). \tag{1}$$

q_{VP} is the momentum of the vector meson or the pseudoscalar, and $\mathcal{F}$ is the form factor. For channels that cannot be produced through $c\bar{c} \to ggg$, with the remaining open avenue for $\psi(3770)$ decay being $c\bar{c} \to \gamma^*$, which is severely suppressed, the event yield on the $\psi(3770)$ will be entirely attributable to continuum production, $e^+e^- \to \gamma^*$, as for $\omega\pi^0$, $\rho\eta$, and $\rho\eta'$. All our measurements are either firsts of their kind or consistute an improvement over previous measurements. Other $\psi(3770)$ non-$D\bar{D}$ decay channels are covered in separate articles [7].

The data analyzed here were collected with the CLEO detector [8] operating at the Cornell Electron Storage Ring (CESR) [9]. The CLEO detector features a solid angle coverage of 93% for charged and neutral particles. The charged particle tracking system operates in a 1.0 T magnetic field along the beam axis and achieves a momentum resolution of $\sim 0.6\%$ at momenta of $1\,\mathrm{GeV}/c$. The CsI crystal calorimeter attains photon energy resolutions of 2.2% for $E_\gamma = 1\,\mathrm{GeV}$ and 5% at 100 MeV. Two particle identification systems, one based on energy loss (dE/dx) in the drift chamber and the other a ring-imaging Cherenkov (RICH) detector, together are used to separate kaons from pions. The combined dE/dx-RICH particle identification procedure has a pion or kaon efficiency >90% and a probability of pions faking kaons (or vice versa) <5%.

We base our event selection on charged particles reconstructed in the tracking system and photon candidates in the CsI calorimeter. Energy and momentum conservation is required of the reconstructed hadrons, which have momenta p_i and total energy E_{vis}. We demand $0.98 < E_{\mathrm{vis}}/E_{\mathrm{cm}} < 1.015$ and $||p_1|-|p_2||/E_{\mathrm{beam}} < 0.04$, which together suppress backgrounds with missing energy or incorrect mass assignments. The experimental resolutions are smaller than 1% in scaled energy and 2% in scaled momentum difference. In order to suppress hadronic transitions to J/ψ, we reject events in which any of the following fall within 3.05-3.15 GeV: the invariant mass of the two highest momentum tracks; or the recoil mass from the lowest momentum single π^0, $\pi^0\pi^0$ pair, or $\pi^+\pi^-$ pair. Feeddown from $\pi^0\pi^0 J/\psi$, $J/\psi \to \mu^+\mu^-$ into $\pi^+\pi^-\pi^0$, $\rho^+\pi^-$, or $(K^+\pi^0)K^-$ is additionally suppressed by requiring $M(\mu^+\mu^-) < 3.05$ GeV for those channels.

MC studies were used to determine invariant mass windows for intermediate particle decay products: π^0 ($M_{\gamma\gamma}$=110-150 MeV), η ($M_{\gamma\gamma}$, $M_{\pi^+\pi^-\pi^0}$=520-580 MeV), η' ($M_{\pi^+\pi^-\eta}$=0.92-1.00 GeV), $\bar{K}^0 \to K_S$ ($M_{\pi^+\pi^-}$=490-506 MeV), ω ($M_{\pi^+\pi^-\pi^0}$=740-820 MeV), ρ ($M_{\pi^+\pi^-}$=0.6-1.0 GeV), ϕ ($M_{K^+K^-}$, $M_{\pi^+\pi^-\pi^0}$=0.98-1.06 GeV), K^* ($M_{K\pi}$=0.8-1.0 GeV), and $b_1(1235)$ ($M_{\omega\pi}$=0.96-1.5 GeV). To avoid contamination from $\omega f_2(1270)$ and $\omega f_0(600)$ [10] in $b_1\pi$, we exclude $M_{\pi\pi}$ <1.5 GeV. Similarly, $\rho\eta$ candidates with low mass $\eta\pi^\pm$ states are avoided with $M(\eta\pi^\pm)_{\mathrm{min}} > 1.4$ GeV. For $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$, and $K_S \to \pi^+\pi^-$ candidates we use kinematically constrained fits to the known parent masses and, for $K_S \to \pi^+\pi^-$, a fit of the $\pi^+\pi^-$ trajectories to a common vertex separated from the e^+e^- interaction ellipsoid. Fake π^0's and η's are suppressed with lateral shower profile restrictions and by requiring that their decays to $\gamma\gamma$ not be too asymmetric: $|\cos\alpha| < 0.95$, where α is the angle in the π^0 or η center of mass between either photon and its parent's momentum vector.

For $\pi^+\pi^-\pi^0$, $\rho^+\pi^-$, and $\rho\eta$ ($\phi\eta$), one of the two charged particles must be positively identified as a $\pi^\pm$ ($K^\pm$), but neither can be positively identified as a $K^\pm$ ($\pi^\pm$). Charged kaons in K^*K must be identified as such, and any $\pi^\pm$ candidate must not be identified as $K^\pm$. Charged particles must not be identified as electrons using criteria based on momentum, calorimeter energy deposition, and dE/dx. The softer charged particle in two-track modes must have $p < 0.85 \times E_{\mathrm{beam}}$. Both tracks in two-track modes must satisfy $|\cos\theta| < 0.83$, where θ is the polar angle with respect to the e^+ direction. We present distributions of scaled total energy and reconstructed invariant masses for selected modes in Figures 1-3.

The efficiency ϵ for each final state is obtained from MC [11, 12]. The VP modes are generated with angular distribution $(1 + \cos^2\theta)$ [13], $b_1\pi$ flat in $\cos\theta$, and $\pi^+\pi^-\pi^0$ as in ω decay. We assume $\mathcal{B}(b_1 \to \omega\pi)$=100%.

Systematic uncertainties on the cross-section measurements arise from various sources, some common to all channels, some channel specific: The systematic errors on branching fraction ratios share common contributions from the uncertainty in luminosity (1%), trigger efficiency (1%), and electron veto (0.5%). Other sources vary by channel, including cross-feed adjustments (50% of each subtraction), MC statistics, accuracy of MC-generated polar angle and mass distributions (5% for $b_1\pi$, 14% for $\pi^+\pi^-\pi^0$), and detector performance modeling quality: charged particle tracking (1%/track), π^0/η and K_S finding ($2\%/(\pi^0/\eta)$, $5\%/K_S$), π/K identification (3%/identified π/K), and resolutions of mass (2%) and total energy cut (1%). Furthermore, an uncertainty on the adjustment for radiative corrections enters (7%).

Systematic uncertainties dominate most of the $\psi(3770)$ and some of the continuum cross-section measurements.

The signal yields at both center-of-mass energies are listed in Table I, separated into signal mass windows and sideband counts. Also listed are the efficiencies and cross-sections. The statistical errors arise from 68%CL intervals. All cross-sections include an upward correction of 20% to account for initial and final state radiation effects.

We now focus on the discrepancy between the on-$\psi(3770)$ yield and expected background in order to determine whether there is significant production from $\psi(3770)$ decays. To arrive at an estimate for the continuum background at $\sqrt{s} = 3.773\,\mathrm{GeV}$, two routes are pursued: Method I. We scale the measured yield (after sideband subtraction) at $\sqrt{s} = 3.67\,\mathrm{GeV}$ by the luminosity ratio, the ratio of efficiencies $(0.88 - 1.00)$, and an assumed dependence of $1/s^3$ of the continuum cross-section, corresponding to a form factor dependence of $1/s$. This method uses data as much as possible, but suffers from the low event yield in the continuum data sample. Using a different power of $1/s$ results in a change of 5.4% in the scale factor per power of $1/s$. Method II: We use a SU(3)-based scaling prediction, whereby the the cross-sections $\sigma(e^+e^- \to VP)$ are linked [14]: $\omega\pi : \rho\eta : K^{*0}\bar{K}^0 : \rho\pi : \rho\eta' : \phi\eta : K^{*+}K^- : \phi\eta' : \omega\eta : \omega\eta' : \phi\pi = 1 : 2/3 : 4/9 : 1/3 : 1/3 : 4/27 : 1/9 : 2/27 : 2/27 : 1/27 : 0$. We compute a unit of cross-section as $\sigma^{SU(3)} = (15.1 \pm 0.5)\,\mathrm{pb}$ by combining our two isospin violating modes with highest statistics, $\omega\pi^0$ and $\rho\eta$ (scaled by 2/3). This results in a very precise prediction, albeit a model-dependent one. No such prediction exists for $\pi^+\pi^-\pi^0$ and $b_1\pi$.

For each channel, both continuum predictions are compared with the on-resonance yield by a method similar to that proposed in [15], whereby the probability that the background with the proper fluctuations happens to result in an event count beyond the observed signal yield is calculated. We find statistical agreement, with a few exceptions. The mode $\phi\eta$ is found to be enhanced over either prediction: The averaged excess is (60.8 ± 11.6) events, corresponding to a cross-section of $\sigma_{\phi\eta}^{\psi(3770)} = (2.4 \pm 0.5 \pm 0.3)\,\mathrm{pb}$, or, using $\sigma(\psi(3770) \to D\bar{D}) = (6.39 \pm 0.20)\,\mathrm{nb}$ and removing the radiative correction factor in $\sigma_{\phi\eta}^{\psi(3770)}$, a branching fraction $\mathcal{B}(\psi(3770) \to \phi\eta) = (3.1 \pm 0.6 \pm 0.3 \pm 0.1) \times 10^{-4}$, where the first error is statistical, the second systematic arising from this measurement, and the third that induced by $\sigma_{D\bar{D}}^{\psi(3770)}$. A suppression with modest statistical significance is observed for $\pi^+\pi^-\pi^0$, $\rho^0\pi^0$, and $K^{*+}K^-$. The enhancement of $K^{*0}\overline{K^0}$ with respect to the SU(3) based prediction is not surprising given that this channel also significantly exceeded the same kind of expectation at $\sqrt{s} = 3.67\,\mathrm{GeV}$ [16]. Additional information on $\pi^+\pi^-\pi^0$ is shown in Figure 4: The dipion invariant masses in $\psi(3770)$ data shows features similar to that of continuum (*i.e.* population of the ρ mass bands together with an accumulation at higher masses); the yield reduction appears uniform in the dipion distribution.

We compute upper limits on the event yields coming from $\psi(3770)$ decays for all modes, where we treat those with a deficit as zero counts, neglecting interference effects, and arrive at an upper limit summed over all channels of 40 pb.

Finally, the measured cross-sections for $\omega\pi^0$, $\rho\eta$, and $\rho\eta'$ are converted into form factor measurements. The results are listed in Table II. Our raw event yields are in agreement with, but more precise than, recent results from BES [17].

In summary, we have sought twelve vector pseudoscalar final states in $281\,\mathrm{pb}^{-1}$ of $\psi(3770)$ data. Combined with $21\,\mathrm{pb}^{-1}$ collected at $\sqrt{s} = 3.67\,\mathrm{GeV}$, we establish cross-section measurements for these channels at both energies. We arrive at the following conclusions: An excess over the continuum expectation for $\phi\eta$, a modest suppression for some other channels, but otherwise broad agreement with the continuum prediction. We find that the sum of $\psi(3770)$ decay cross-sections to final states reported here does not exceed 40 pb at 90%CL. Form factor measurements for $\omega\pi^0$, $\rho\eta$, and $\rho\eta'$ have been presented.

Acknowledgments

We gratefully acknowledge the effort of the CESR staff in providing us with excellent luminosity and running conditions. This work was supported by the National Science Foundation, the U.S. Department of Energy, the Research Corporation, and the Texas Advanced Research Program.

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TABLE I: The number of events N in the mass signal windows ("sw") and sidebands ("sb") in continuum ("3.67 GeV") and $\psi(3770)$ ("3.77 GeV") data; the efficiency ϵ; the level of consistency or significance, expressed in units of standard deviations, between continuum background and observed yield, for the two methods of determining the continuum background described in the text, S^{I} and S^{II}; the cross-sections at $\sqrt{s} = 3.67$ GeV and $\sqrt{s} = 3.773$ GeV.

Channel	$N_{\mathrm{sw}}^{3.67}$	$N_{\mathrm{sb}}^{3.77}$	$N_{\mathrm{sw}}^{3.77}$	$N_{\mathrm{sb}}^{3.67}$	ϵ	S^{I}	S^{II}	$\sigma^{3.67\mathrm{GeV}}$ [pb]	$\sigma^{3.77\mathrm{GeV}}$ [pb]
$\pi^+\pi^-\pi^0$	74	7	576	72	0.29	2.7	–	$13.1^{+1.9}_{-1.7} \pm 2.1$	$7.4 \pm 0.4 \pm 1.2$
$\rho^0\pi^0$	21	3	130	33	0.33	2.2	2.2	$3.1^{+1.0}_{-0.8} \pm 0.4$	$1.3 \pm 0.2 \pm 0.2$
$\rho^+\pi^-$	22	2	184	12	0.23	0.9	0.6	$4.8^{+1.5}_{-1.2} \pm 0.5$	$3.2 \pm 0.3 \pm 0.3$
$\rho\pi$	43	5	314	45	0.26	2.2	1.9	$8.0^{+1.7}_{-1.4} \pm 0.9$	$4.4 \pm 0.3 \pm 0.5$
$\omega\pi^0$	54	6	696	39	0.19	1.4	0.4	$14.5^{+2.6}_{-2.3} \pm 1.5$	$14.8 \pm 0.6 \pm 1.5$
$\phi\pi^0$	1	2	2	4	0.17	0.0	0.0	< 2.2	< 0.2
$\rho\eta$	36	3	508	31	0.20	1.5	0.5	$9.6^{+2.1}_{-1.8} \pm 1.0$	$10.4 \pm 0.5 \pm 1.0$
$\omega\eta$	4	0	15	6	0.10	1.7	3.0	$2.3^{+1.8}_{-1.1} \pm 0.5$	< 0.8
$\phi\eta$	5	1	132	16	0.11	2.5	≥ 5	< 5.0	$4.5 \pm 0.5 \pm 0.5$
$\rho\eta'$	1	0	27	1	0.03	1.2	1.3	$2.0^{+4.5}_{-1.6} \pm 0.2$	$3.8^{+0.9}_{-0.8} \pm 0.5$
$\omega\eta'$	0	0	2	0	0.02	≥ 5	0.0	< 17.1	$0.6^{+0.7}_{-0.3} \pm 0.6$
$\phi\eta'$	0	0	9	2	0.01	2.4	1.2	< 12.6	< 5.2
$K^{*0}\overline{K^0}$	38	0	501	18	0.09	1.1	≥ 5	$23.5^{+4.6}_{-3.8} \pm 3.1$	$23.5 \pm 1.1 \pm 3.1$
$K^{*+}K^-$	4	1	36	32	0.16	1.4	4.2	< 3.5	< 0.6
$b_1^0\pi^0$	5	3	49	82	0.04	1.2	–	< 17.1	< 2.6
$b_1^+\pi^-$	15	2	219	18	0.18	1.0	–	$4.2^{+1.6}_{-1.3} \pm 0.6$	$4.7 \pm 0.4 \pm 0.6$
$b_1\pi$	20	4	268	67	0.11	0.5	–	$7.9^{+3.1}_{-2.4} \pm 1.8$	$7.6 \pm 0.7 \pm 1.8$

TABLE II: Form factors with statistical and systematic errors.

Channel	$\mathcal{F}(s)$ (GeV^{-1})	
	$\sqrt{s} = 3.670$ GeV	$\sqrt{s} = 3.773$ GeV
$\omega\pi^0$	$0.039 \pm 0.003 \pm 0.002$	$0.040 \pm 0.001 \pm 0.002$
$\rho\eta$	$0.033 \pm 0.003 \pm 0.002$	$0.034 \pm 0.001 \pm 0.002$
$\rho\eta'$	< 0.038 (90%CL)	$0.022^{+0.003}_{-0.002} \pm 0.001$

FIG. 1: Scaled visible energy $E_{\rm vis}/E_{\rm cm}$ for selected final states. Circles: $\psi(3770)$ data, shaded histogram: scaled continuum, dashed histogram: signal MC, arbitrary normalization. Arrows indicate selection intervals.

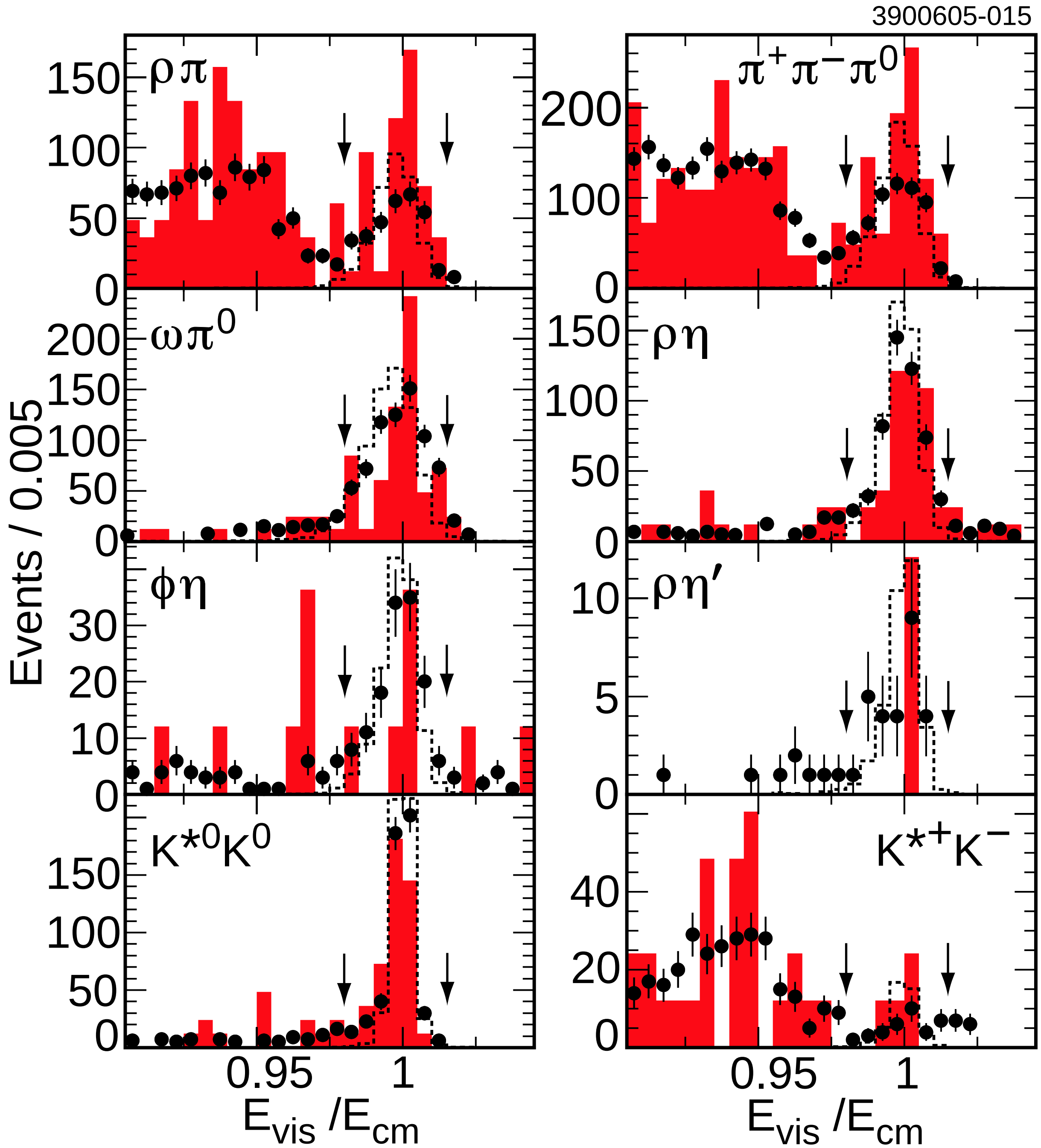

FIG. 2: Reconstructed invariant mass distributions for selected final states. Symbols as in Fig. 1.

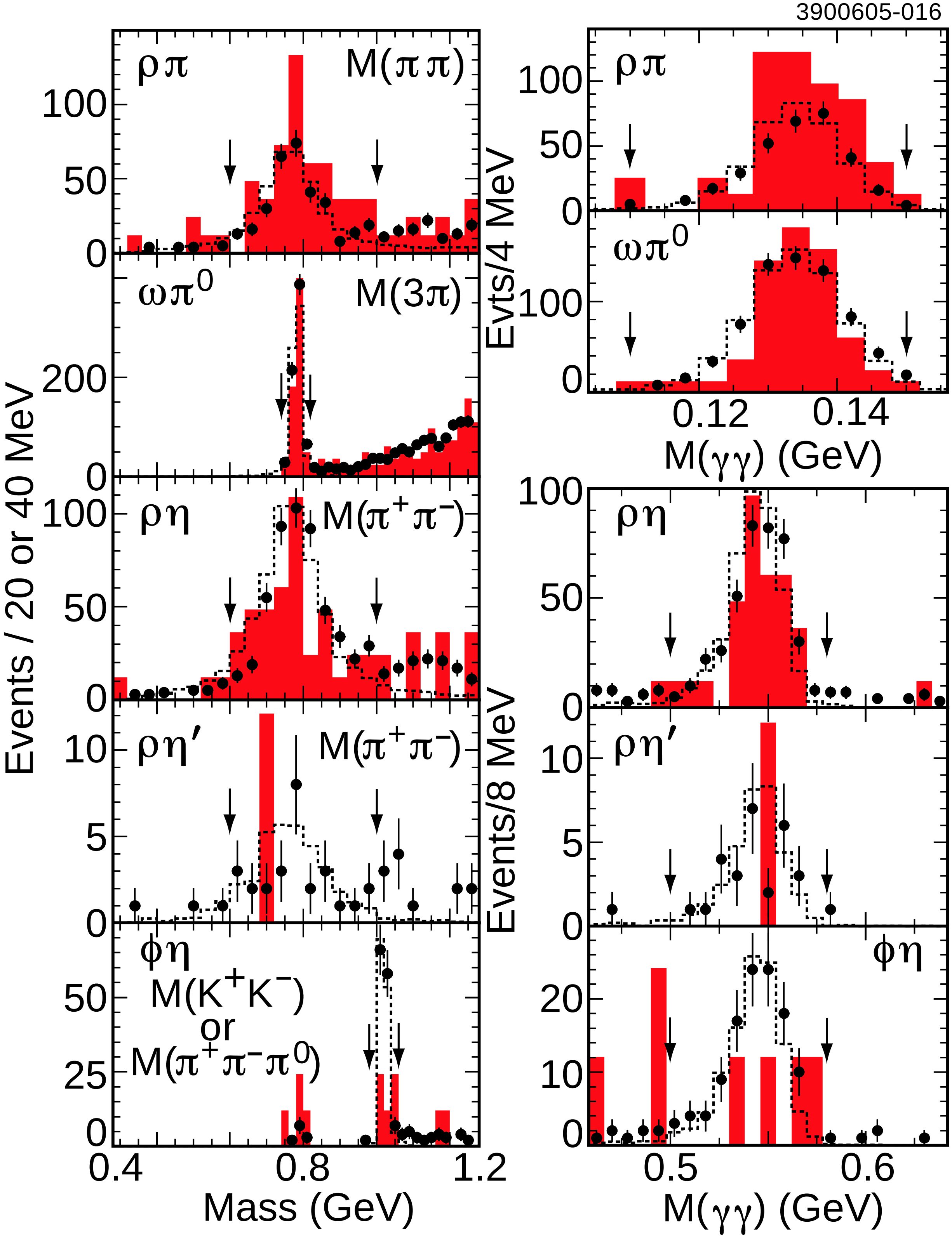

FIG. 3: Mass distributions for selected final states, continued. Symbols as in Fig. 1.

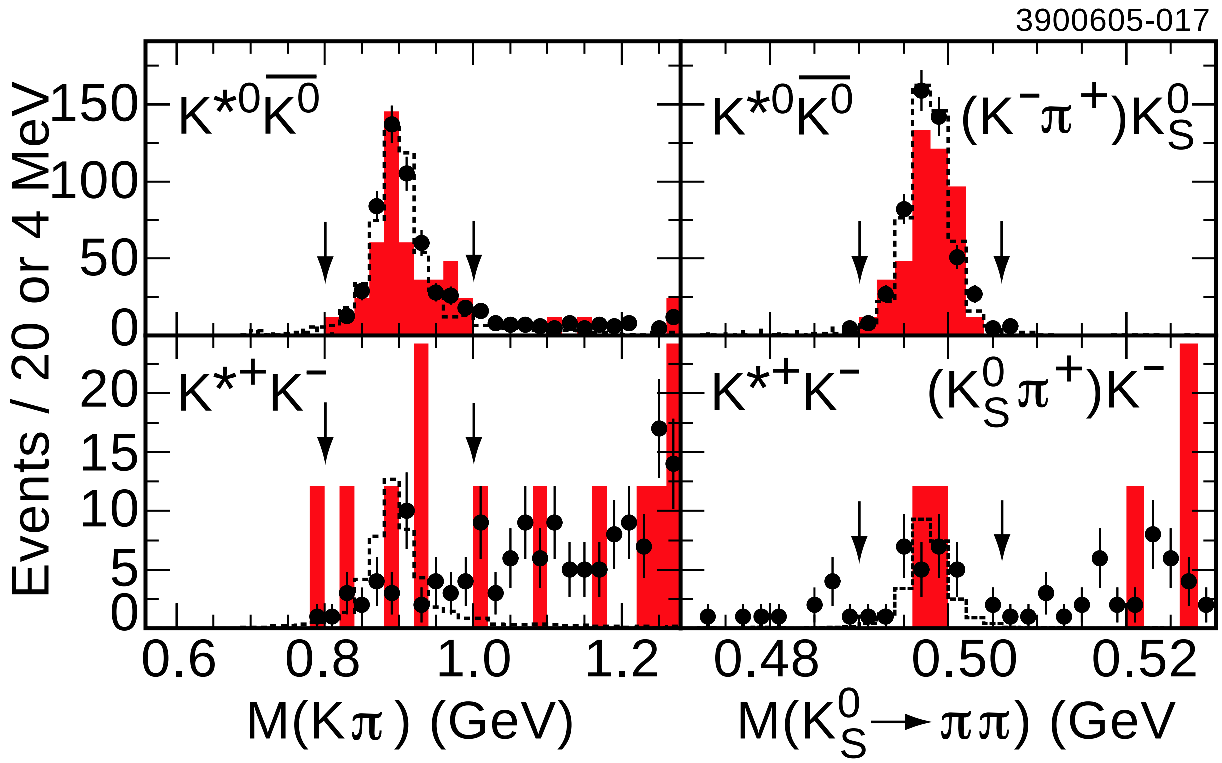

FIG. 4: Dipion invariant mass distributions for the $\pi^+\pi^-\pi^0$ final state in (a) $\psi(3770)$ data, (b) continuum data. (c) The invariant mass of all pion pairs per event and (d) the reconstructed π^0 mass, in $\psi(3770)$ data (circles), scaled continuum data (shaded histogram), and phase space MC (dashed line).